Beam Halo Formation in High-Current Proton Beams

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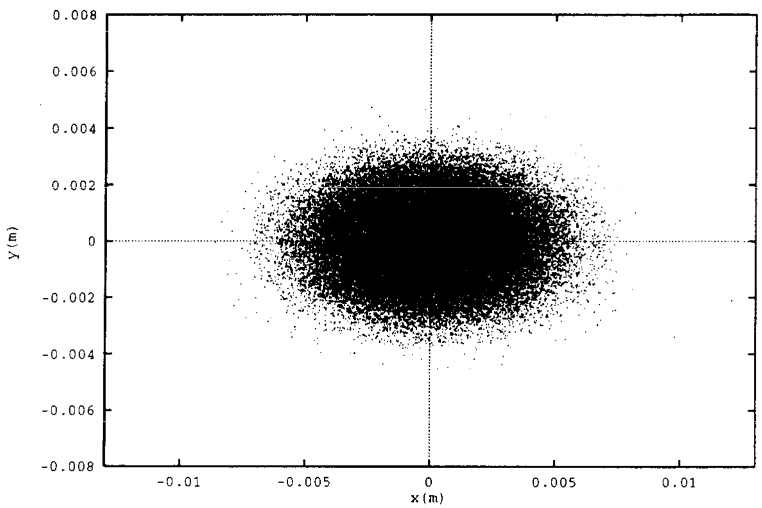
and the LEDA Halo Experiment Team

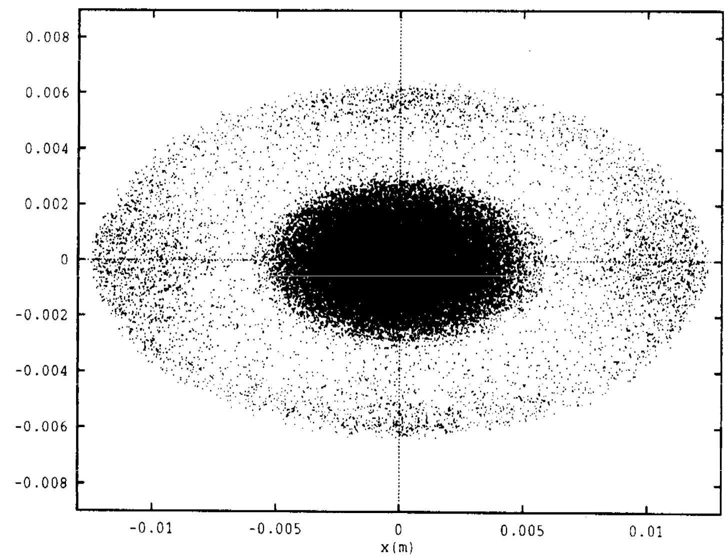
Introduction and Outline

- Computer simulations and linac operating experience show that a small fraction of particles can acquire a large transverse energy to form halo.
- Halo particles can induce radioactivity, a major concern for new generation of high-intensity proton linacs (ATW, SNS).
- The cause of halo had remained a mystery since LAMPF was built (1972).
- During the past decade a theoretical framework was developed based on computer simulation and a particle core model. *I will review the present understanding.*
- A beam halo experiment is now in progress at Los Alamos to test our simulation codes and our understanding. *I will describe the experiment and show some preliminary results.*

Example of Beam Halo --Simulation of beam transport line with quadrupole focusing shows that halo is formed in mismatched beams.

Rms mismatched beam (on right) develops larger amplitudes than rms matched beam (on left)





Beam mismatch creates extended halo

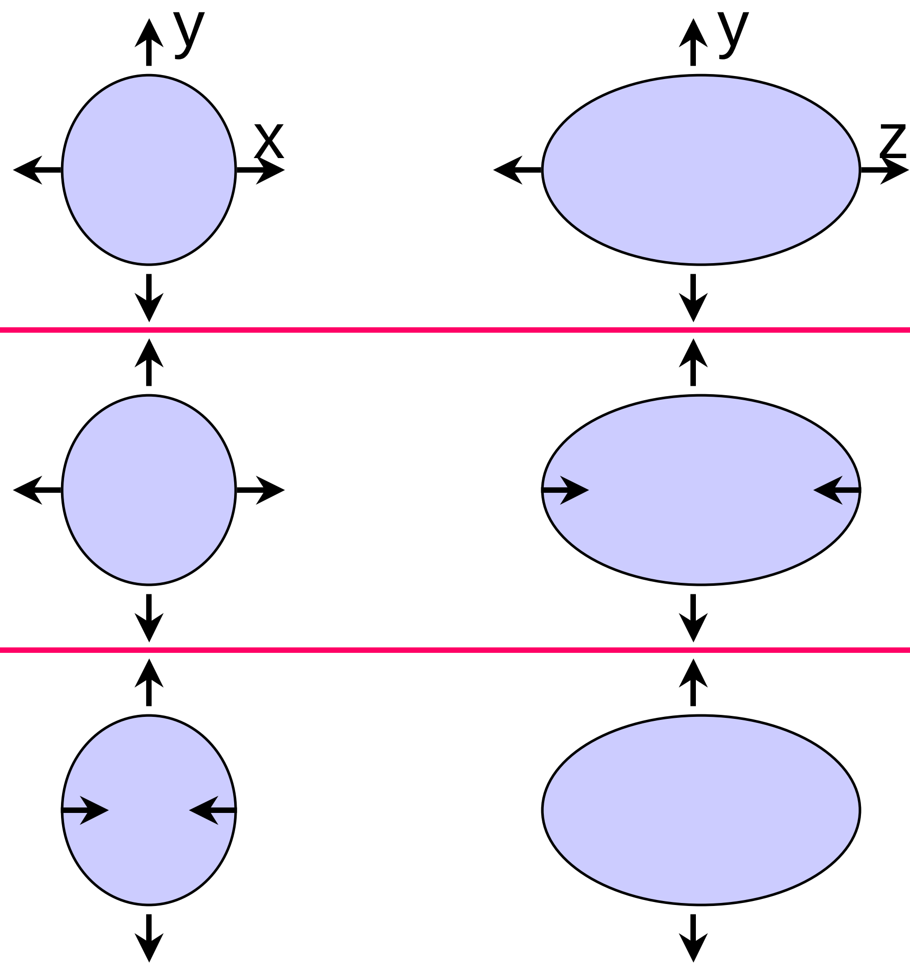
- Beam matching produces a desirable balance between focusing and defocusing forces.
- Beam mismatch produces an imbalance resulting in excitation of rms envelope modes of the beam and immediate increase in particle amplitudes.
- Individual beam particles executing betatron motion through the oscillating beam core can gain transverse energy from the space-charge force.
- Such particles are slowly driven to even larger amplitudes through a space-charge parametric resonance with the core oscillations (shown by Gluckstern).
- Analytic particle-core models have been constructed for different bunch geometries to describe the resonant behavior of the halo particles.

Envelope Modes of Mismatched Bunched Beams

Symmetric
(Breathing)
Mode

Antisymmetric Mode

Quadrupole Mode



Details of Particle-Core Model

- Envelope equation models dynamics of the beam core.
- Mismatch the initial core size to excite an "envelope" oscillation mode such as the breathing mode.
- Introduce test particles that experience non-linear space-charge field of oscillating core.
- As particle amplitude increases, particle frequency increases.
- Particles with frequency $f = f_{mode}/2$ are slowly driven by space-charge of oscillating core to form more extended halo.

Equations for Sphere Particle/Core Model

(Other models include cylinder, and 2D and 3D ellipsoids)

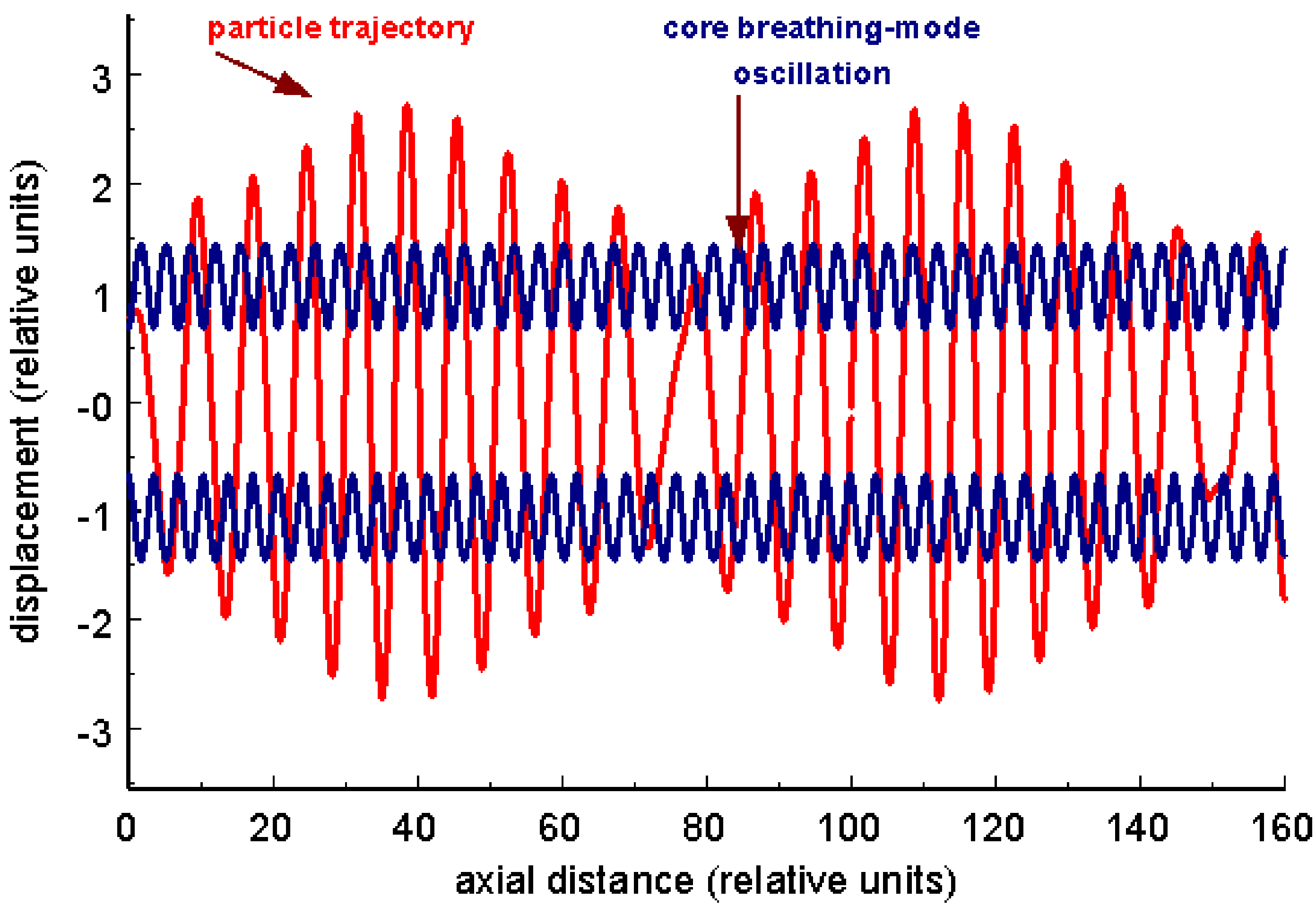
$$R'' + k_0^2 R - \frac{(4\varepsilon_{rms})^2}{R^3} - \frac{\kappa}{R^2} = 0, \text{ envelope equation}$$

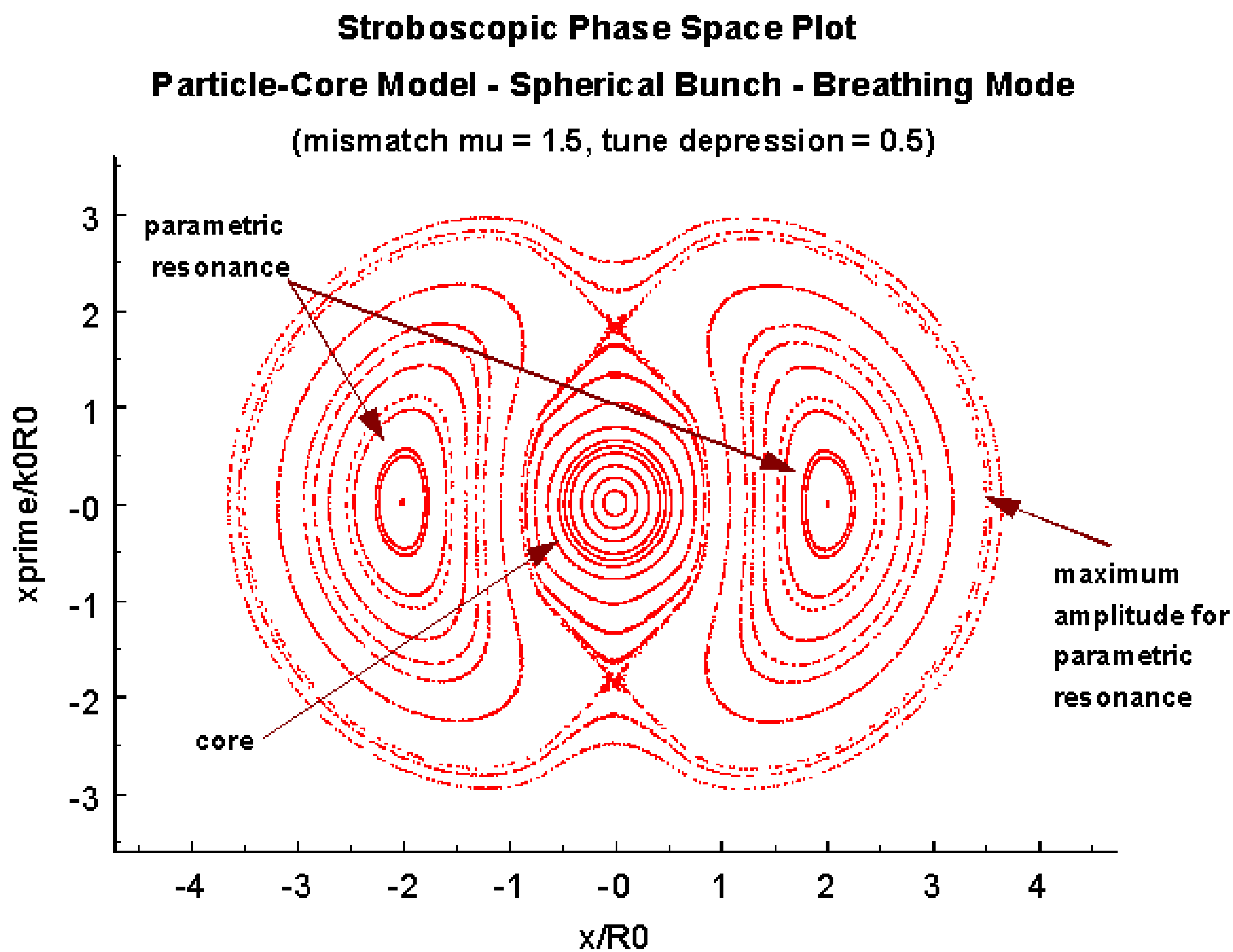
$$\text{where } \kappa = \frac{q^2 N}{4\pi\varepsilon_0 mc^2\gamma^3\beta^2}, \text{ space-charge parameter.}$$

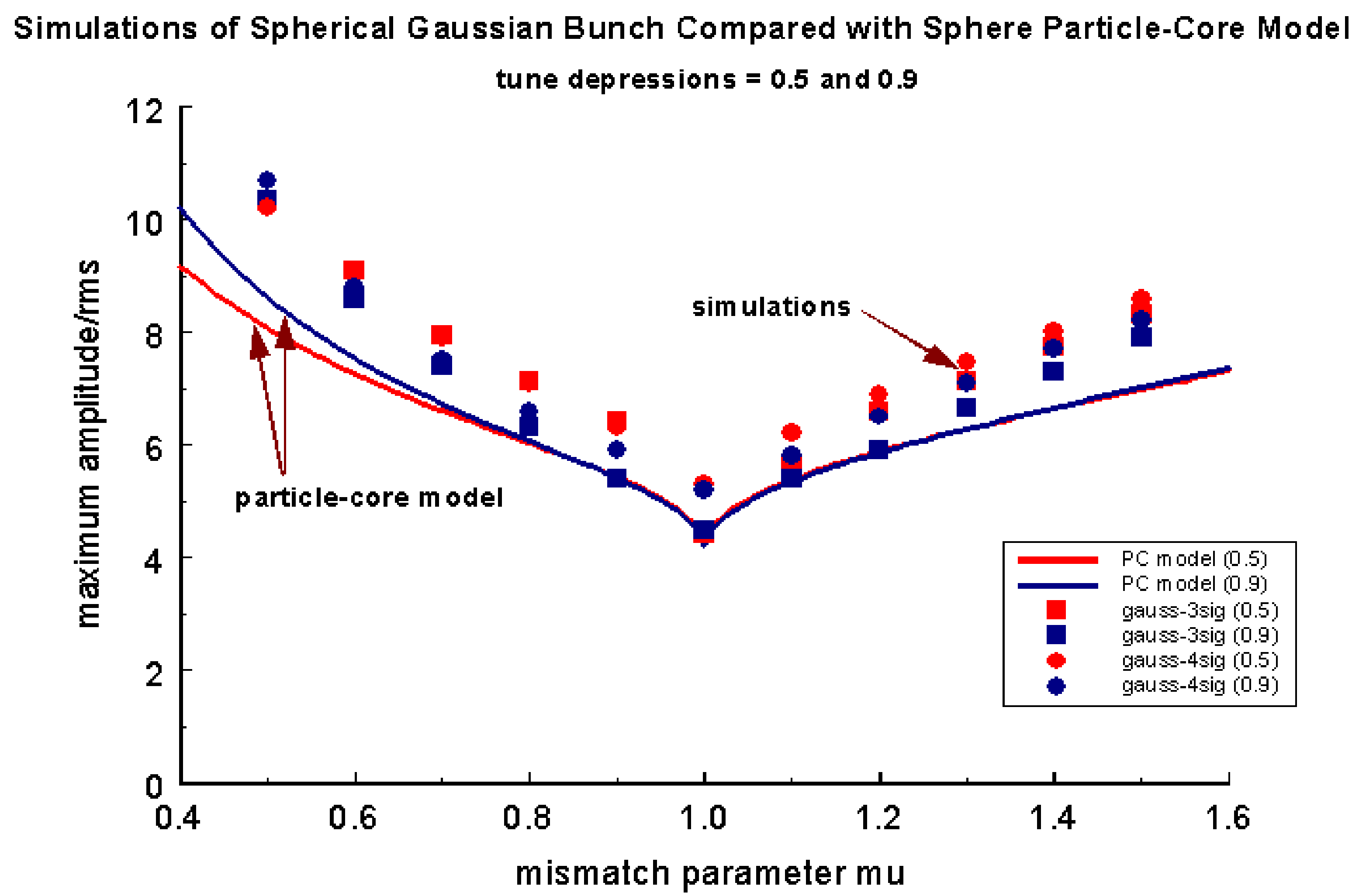
$$x'' + k_0^2 x - \frac{\kappa x}{R^3} = 0, \; x < R, \text{ particle inside of core}$$

$$x'' + k_0^2 x - \frac{\kappa |x|}{x^3} = 0, \; x > R, \text{ particle outside of core.}$$

Parametric Resonance in Sphere Particle-Core Model




Stroboscopic Phase Space Plot
Particle-Core Model - Spherical Bunch - Breathing Mode
(mismatch mu = 1.5, tune depression = 0.5)
parametric
resonance
core
maximum
amplitude for
parametric
resonance
xprime/k0R0
x/R0
3
2
1
-0
-1
-2
-3
-4
-3
-2
-1
-0
1
2
3
4



Simulations of Spherical Gaussian Bunch Compared with Sphere Particle-Core Model
tune depressions = 0.5 and 0.9
maximum amplitude/rms
mismatch parameter mu
0
2
4
6
8
10
12
0.4
0.6
0.8
1.0
1.2
1.4
1.6
simulations
particle-core model
PC model (0.5)
PC model (0.9)
gauss-3sig (0.5)
gauss-3sig (0.9)
gauss-4sig (0.5)
gauss-4sig (0.9)

Scaling of maximum resonant amplitude from sphere particle-core model suggests design guidelines.

$$x_{max} \cong 5\sqrt{\frac{\varepsilon_n}{k_0\beta\gamma}\left[1+u\right]^{2/3}}\left[1+\left|\ln(\mu)\right|\right],$$

where

$$u = \frac{q^2 N}{20\sqrt{5}\pi\varepsilon_0 mc^2\left(k_0\beta\gamma^3\varepsilon_{n,rms}^3\right)^{1/2}}.$$

μ = match parameter

β, γ = velocity, relativistic mass factor

N = particles per bunch

$\varepsilon_{n,rms}$ = rms normalized emittance

k_0 = zero – current transverse wave number

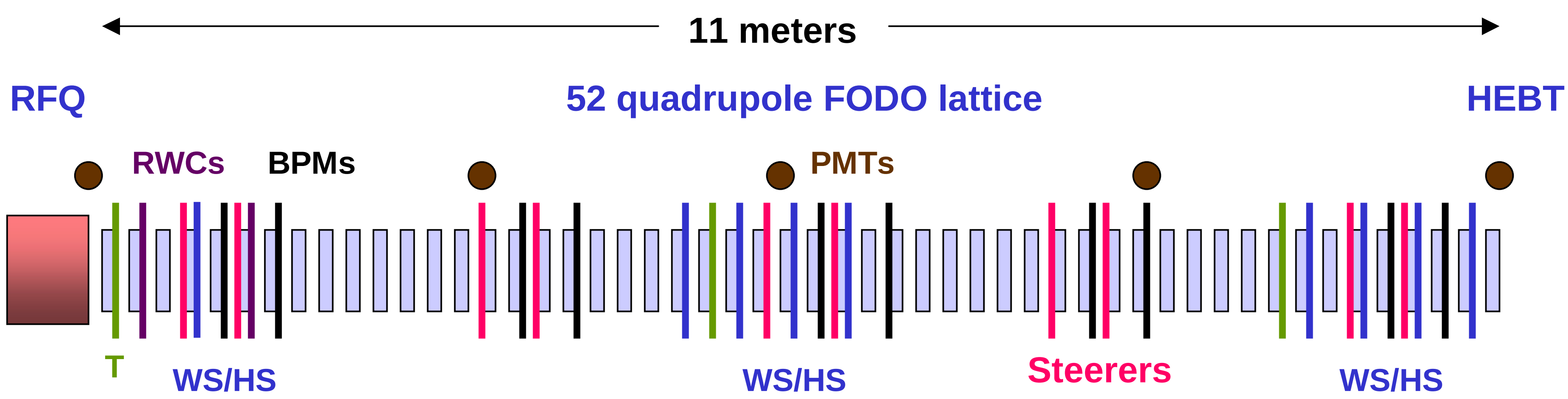
Particle-core model summary

- Halo extent is limited because of the amplitude-dependence of particle-oscillation frequency (simulations confirm this as a good approximation).
- Growth rate of halo increases as beam becomes more space-charge dominated).
- Ellipsoidal models (Maryland, LLNL, and LANL) show bunch aspect ratio dependence. For z>2r symmetric (breathing) mode generates mostly transverse halo. Antisymmetric mode generates mostly longitudinal halo.
- Rf nonlinear force disrupts the parametric resonance condition for longitudinal halo. *(J. Barnard and S. Lund).* Simulations confirm that longitudinal halo is well confined within rf bucket.
- Scaling formula shows that to limit the halo you want strong focusing, good matching, and high frequency.

Beam-Halo Experiment

- 75-mA pulsed beam (~30-μsec pulse, 1-Hz) from 6.7-MeV RFQ at LEDA facility.
- FODO transport line with 52 quadrupoles and ample compliment of beam diagnostics.
- First four quadrupoles are used to create breathing- and quadrupole-mode mismatches.
- 10 mismatch oscillations, enough to produce measurable halo growth as predicted by simulations.
- Use special beam-profile scanners consisting of a thin wire for core measurement and plates for halo measurement. Large dynamic intensity range for beam profile (at least 10000).
- Vary mismatch and current. Measure and compare with codes 1) **rms emittances,** 2) **maximum detectable amplitudes**, 3) **kurtosis** (beam profile parameter).
- Also search for additional halo from other sources.

Fully Instrumented LEDA Beam-Halo Lattice



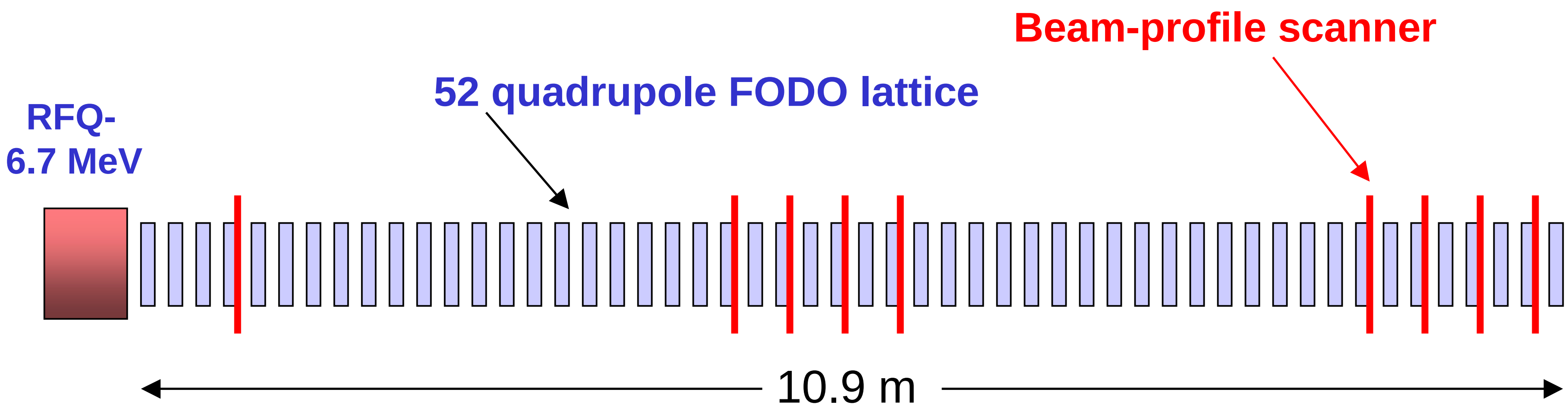
First 4 quadrupoles independently powered for generating mismatch modes.

52 Quadrupoles + 4 in the HEBT
9 Wire Scanners/Halo Scrapers (Projections) + 1 in the HEBT
3 Toroid (Pulsed Current) + 2 in the HEBT
5 PMT Loss Monitors (Loss) + 2 in the HEBT
10 Steering Magnets + 2 in the HEBT
10 Beam Position Monitors (Position) + 5 in the HEBT
2 Resistive Wall Current Monitors (Central Energy)

LEDA Facility Halo Lattice

Close Up of WS #45 through WS #51

Beam-halo experiment



Halo Experiment Scientific Team

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Beam profile monitor is our main halo diagnostic tool (J.D.Gilpatrick, et al.)

- 9 measurement stations at which both horizontal and vertical projected distributions are measured.
- Wire is 33μ carbon fiber to measure core.
  -Stopping range of protons is 300μ so protons pass through wire.
  -Wire signal is due to secondary electron emission.
  -Wire bias voltage about -10V to enhance signal.
- Scraper is graphite plate brazed onto copper. Scraper measures halo
  -Graphite is 1.5 mm thick so protons stop in graphite.
  -Scraper bias voltage about +10V to suppress secondary electron emission.
  -Copper is water cooled.
- Simulations predicted dynamic range of 10^3:1 for wire alone and 10^5:1 for wire plus scraper. Approximately confirmed by observations.
- Simulations predicted wire can detect to 4 rms. Halo scraper extends this to 5 rms.

Measurement Cycle

- RF blanking pulse de-energizes RFQ.
- 75-keV beam from dc injector is injected into unpowered RFQ as injector beam approaches steady state.
- RF blanking pulse is removed and RFQ is excited. (T~5μs rise time)
- Beam profile monitors are in fixed position so only one wire or scraper is in beam at a time. All other wires or scrapers are outside beam pipe aperture.
  -Wire or scraper collects beam-induced charge over about 30μs
  -30μs limit is set by onset of thermionic emission of the scanner wire.
  -Accumulated charge is digitized.
  -Only last 10μs of collected charge is selected for data.
- After 30μs interval dc injector turned off.
- During 1 sec before next pulse, scanner wire and scraper are moved to next position.

Procedures for Matching and Mismatching are Important

- Beam matching is being done initially by adjusting the first 4 quadrupoles to produce equal rms sizes in x and equal rms sizes in y at the four scanners in the middle of the channel.
  -A least squares fitting procedure is used.
- Pure mode mismatches are then done by calculating matched Courant-Snyder ellipse parameters at the scanners using TRACE3D.
  -Then, adjust the first 4 quadrupoles to set these parameter values.
  -Equal scale factors for x and y planes produce pure breathing mode.
- Mismatch strength measured using parameter μ which equals ratio of initial rms size of mismatched beam to rms size of matched beam.

Characterization of the Beam from the Profile Measurements

- Rms emittances at RFQ exit are calculated from a least squares procedure using rms-size measurements at upstream beam profile monitor for a array of different settings of the first four matching quadrupoles.
- Rms emittances at the two clusters of beam profile monitors are calculated from a least squares procedure using rms-size measurements at the four beam profile monitors in each cluster.
- Maximum detectable amplitude is determined from intersection of transverse profile curve with background noise level.
- Shape of distribution is characterized using a “kurtosis” parameter defined in terms of ratio of 4th moment to 2nd moment.

Beam-profile parameter (kurtosis)definition

$$h_x = \frac{\langle x^4 \rangle}{\langle x^2 \rangle^2} - 2.$$

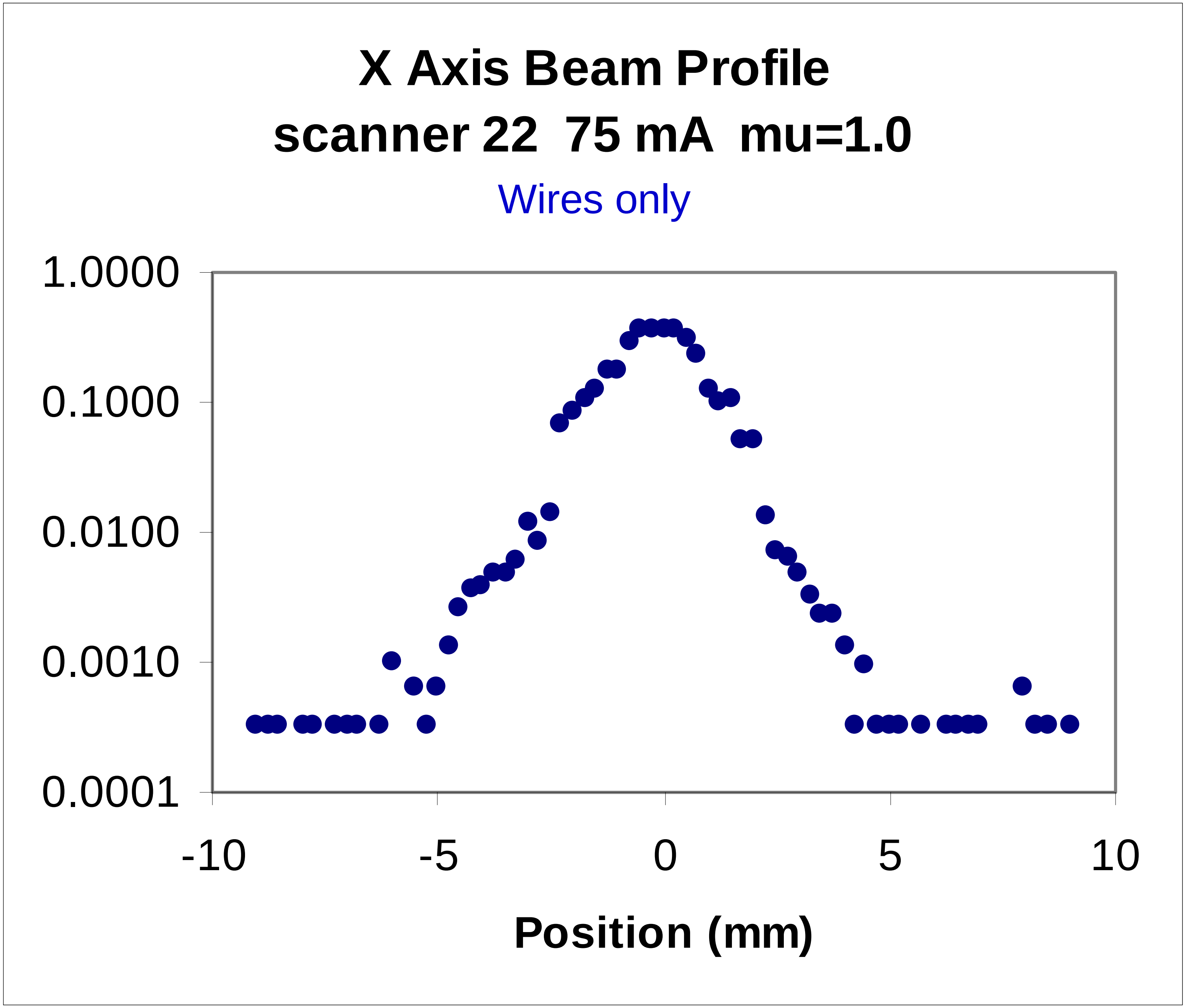
-Similar definition applies for y and z coordinates.
-Dimensionless shape parameters independent of beam intensity.
-Easily calculated from moments of measured or simulated beam profiles.
-Zero for uniform-density 2D elliptical (KV) or 3D ellipsoidal beam.
-Equal to or near unity for Gaussian profile.
-Matched beams without halo have values between 0 and 1.
Increases as tails develop, but can decrease and go negative if beam profile becomes square.

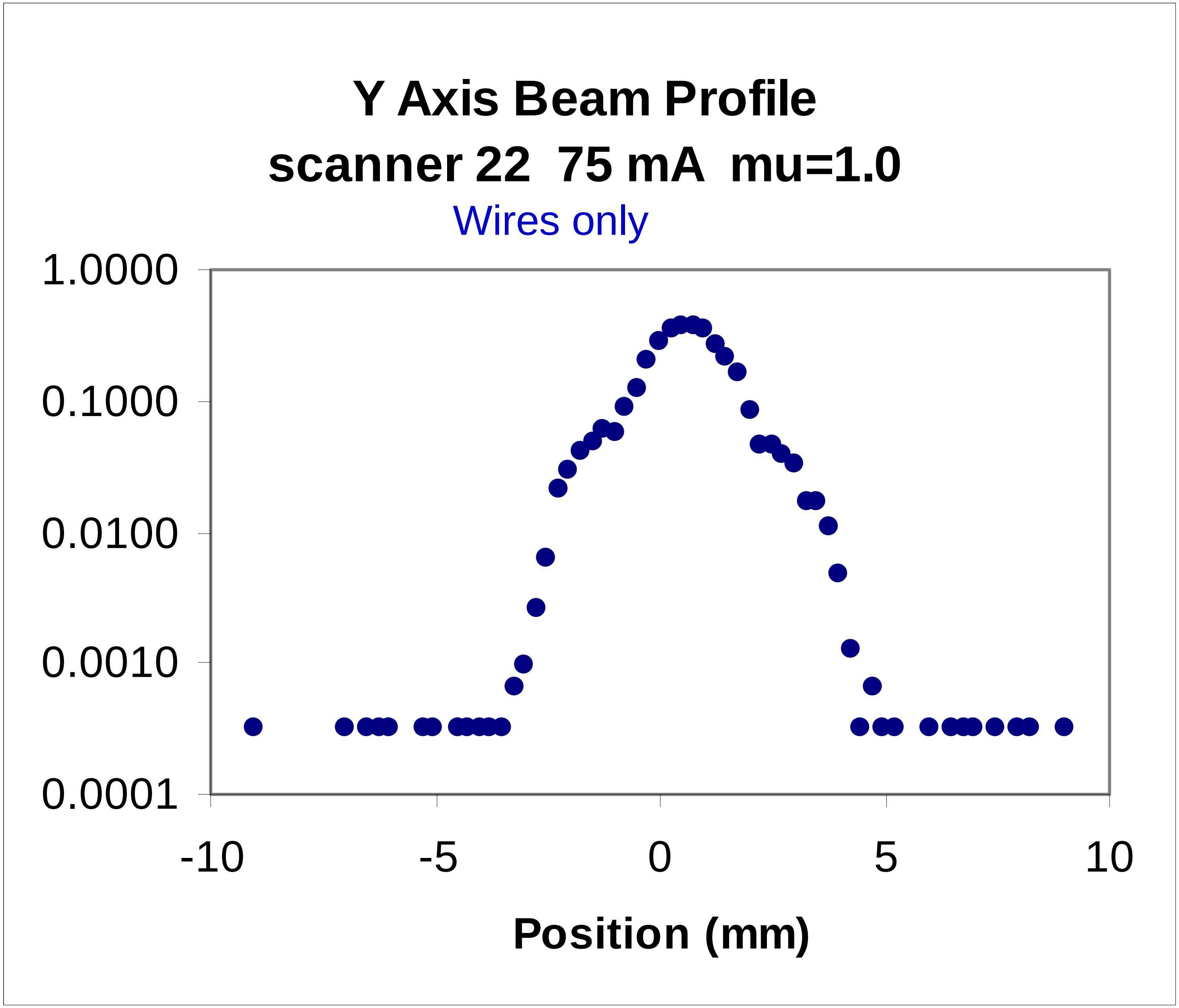
Approximate position measurement errors

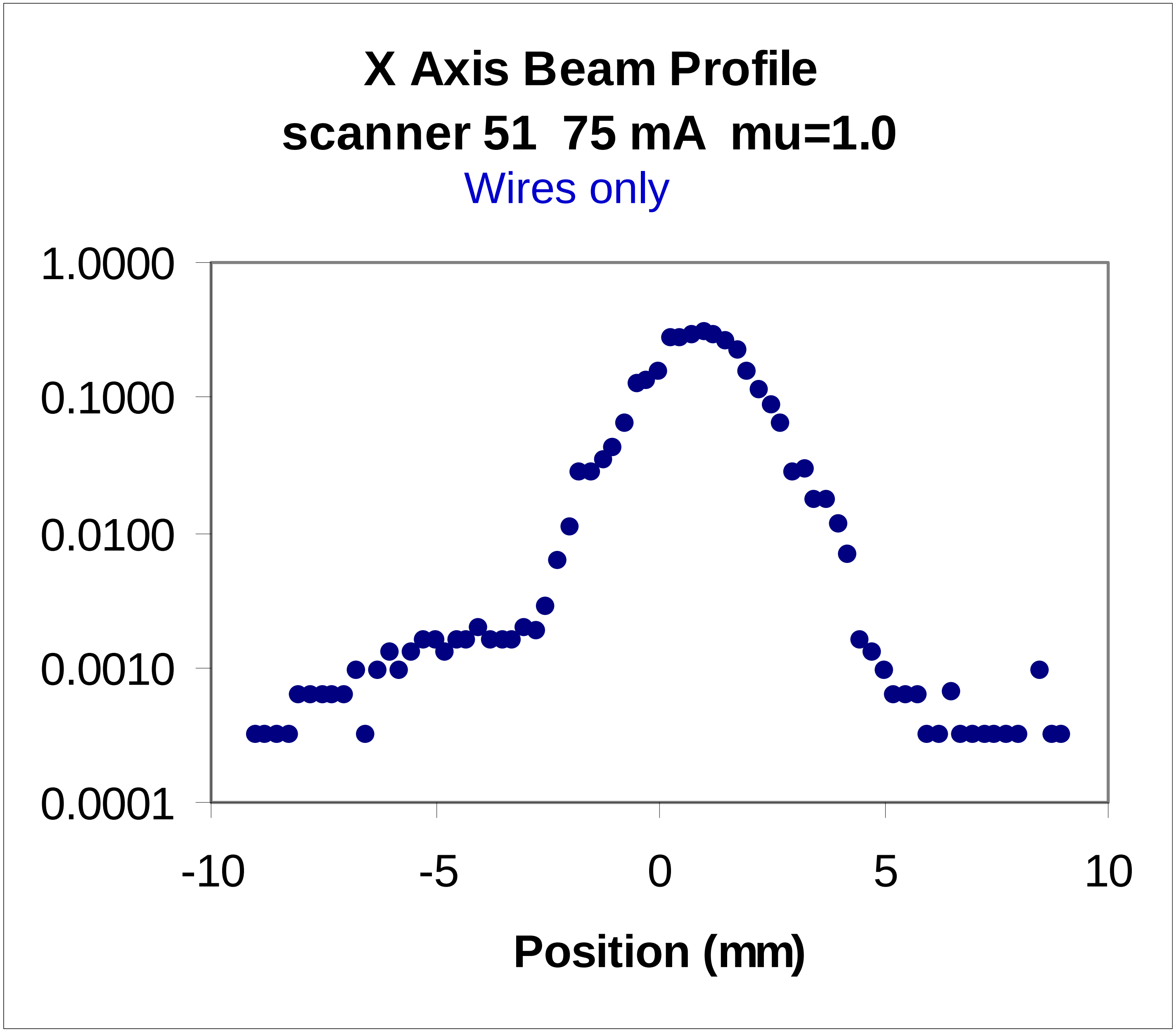
- Beam centering: ±200μ.
- Beam jitter: ±50μ
- RMS beam size: ±50μ

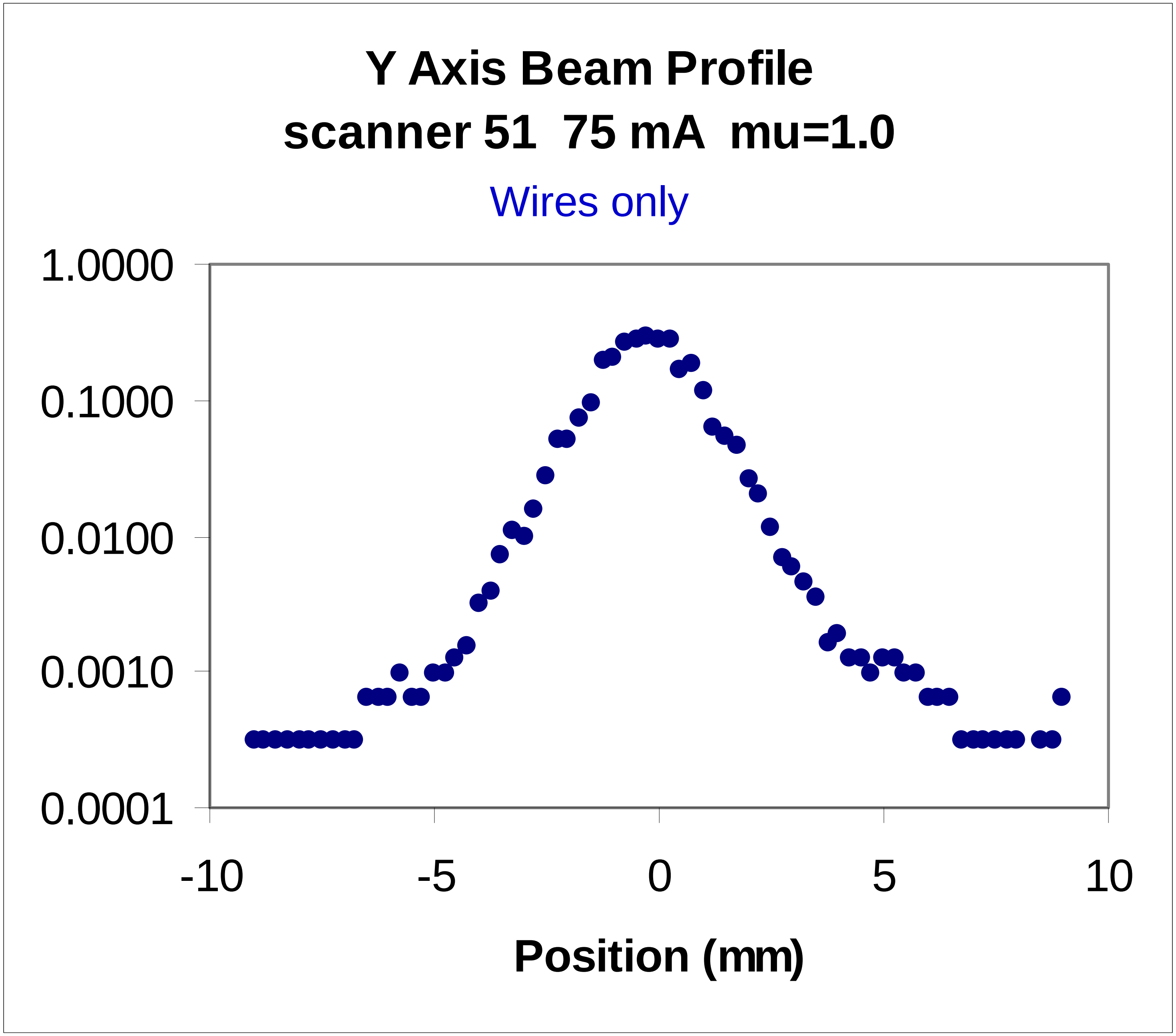
Preliminary results from measured profile shapes at 75 mA

- Measurements have been made at 15, 50, and 75 mA. Initial analysis has been carried out for 75 mA data.
- Transverse profile measurements for mismatched beams show unexpected halo structure.
  -shoulders
  -asymmetries
- Rms-emittance grows along the channel; Growth rate increases as mismatch increases.
- Kurtosis generally decreases with increasing mismatch strength as shoulders develop.
- Maximum detectable amplitude shows no measurable dependence on mismatch strength.

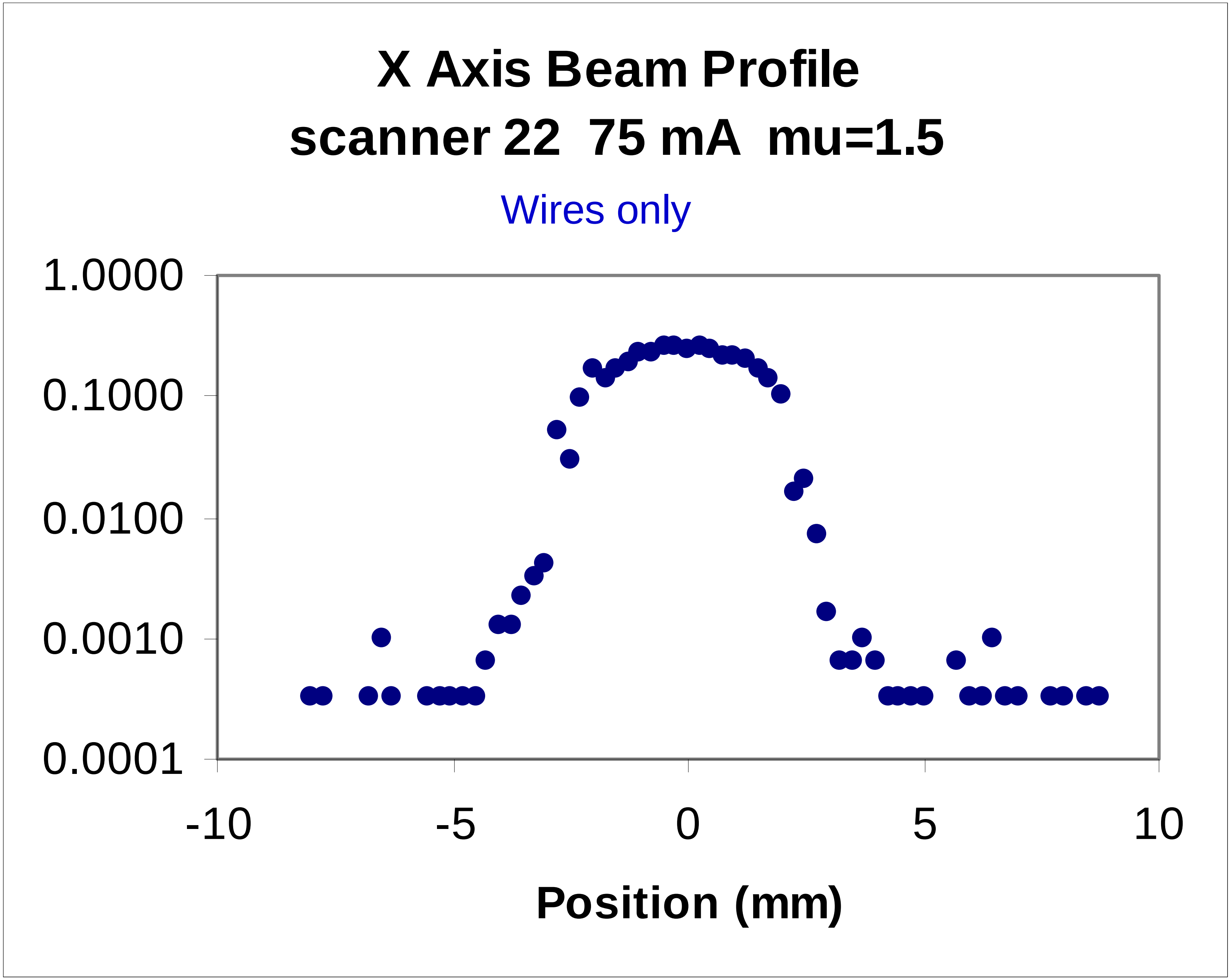

X Axis Beam Profile
scanner 22 75 mA mu=1.0
Wires only
1.0000
0.1000
0.0100
0.0010
0.0001
-10
-5
0
5
10
Position (mm)


Y Axis Beam Profile
scanner 22 75 mA mu=1.0
Wires only
1.0000
0.1000
0.0100
0.0010
0.0001
-10
-5
0
5
10
Position (mm)

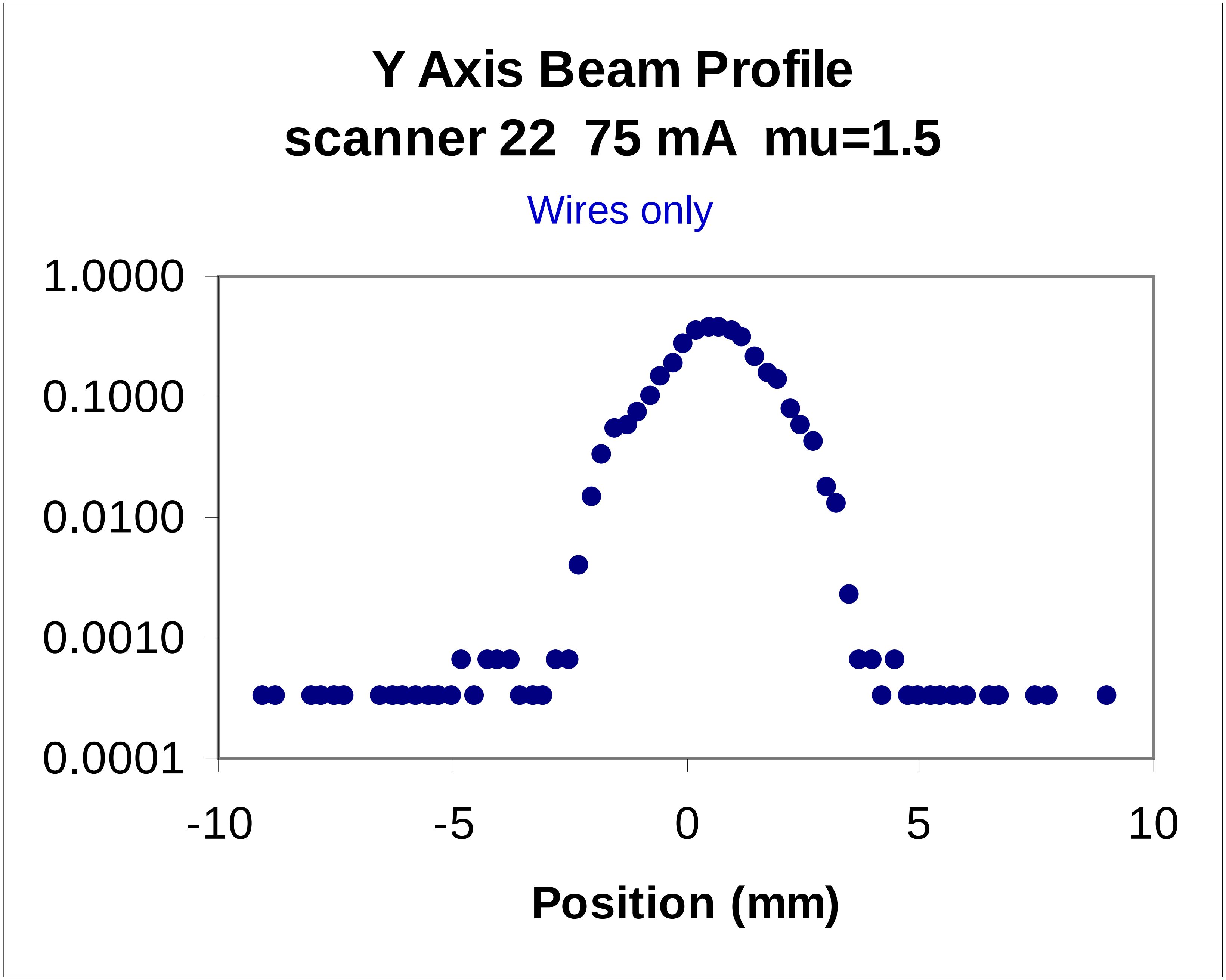

X Axis Beam Profile
scanner 51 75 mA mu=1.0
Wires only
1.0000
0.1000
0.0100
0.0010
0.0001
-10
-5
0
5
10
Position (mm)



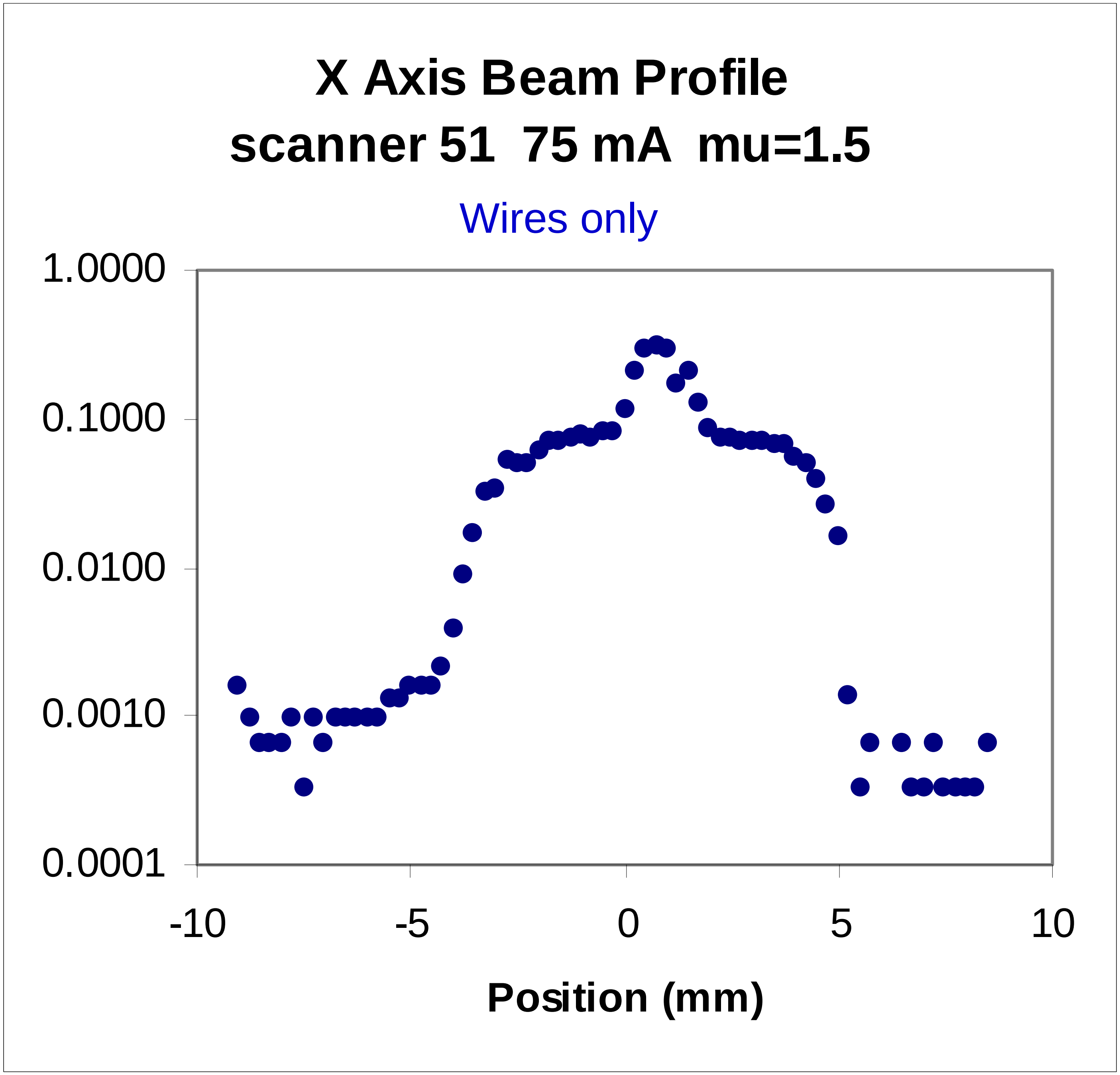
Y Axis Beam Profile
scanner 51 75 mA mu=1.0
Wires only
1.0000
0.1000
0.0100
0.0010
0.0001
-10
-5
0
5
10
Position (mm)

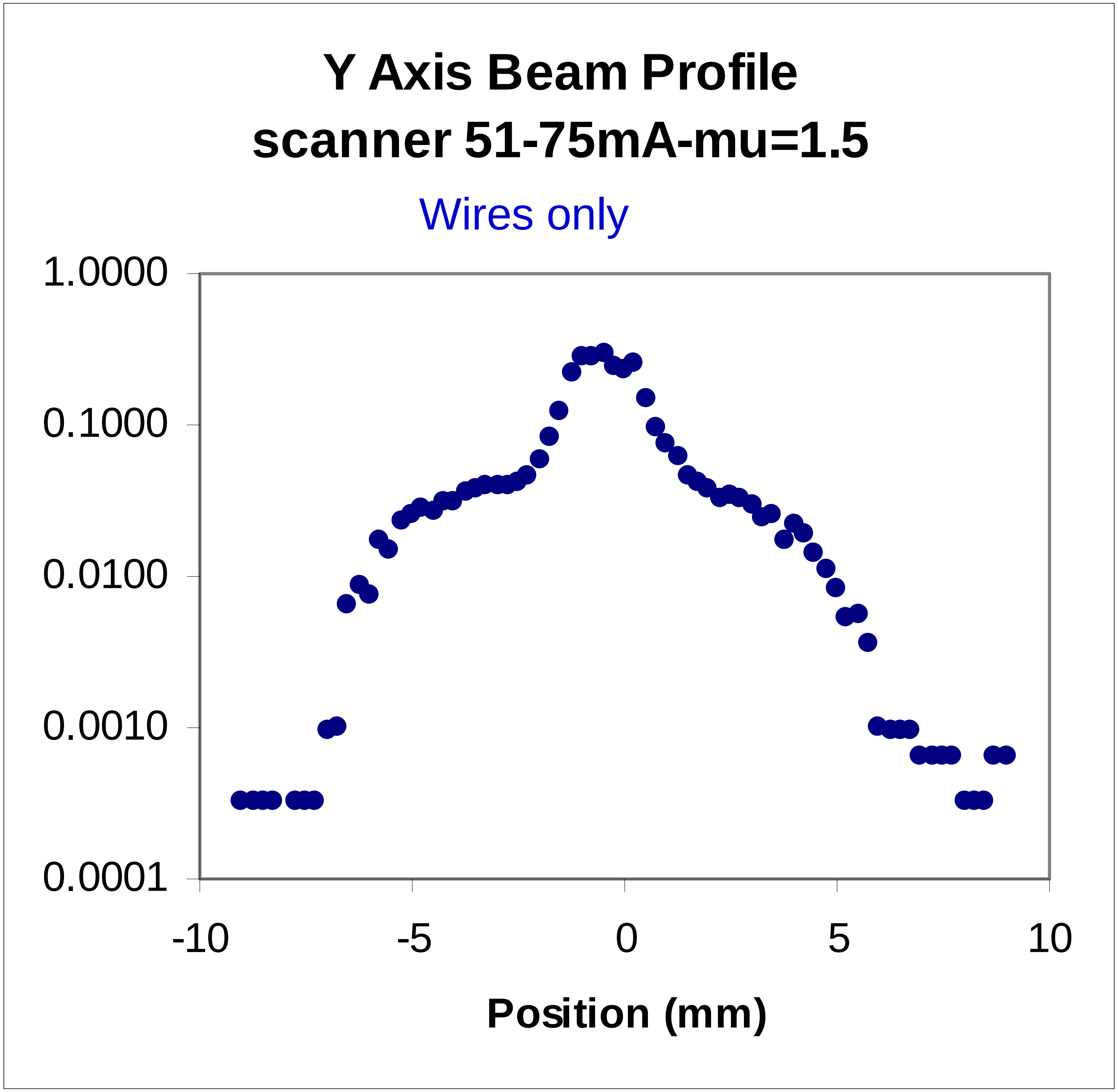


X Axis Beam Profile
scanner 22 75 mA mu=1.5
Wires only
1.0000
0.1000
0.0100
0.0010
0.0001
-10
-5
0
5
10
Position (mm)



Y Axis Beam Profile
scanner 22 75 mA mu=1.5
Wires only
1.0000
0.1000
0.0100
0.0010
0.0001
-10
-5
0
5
10
Position (mm)

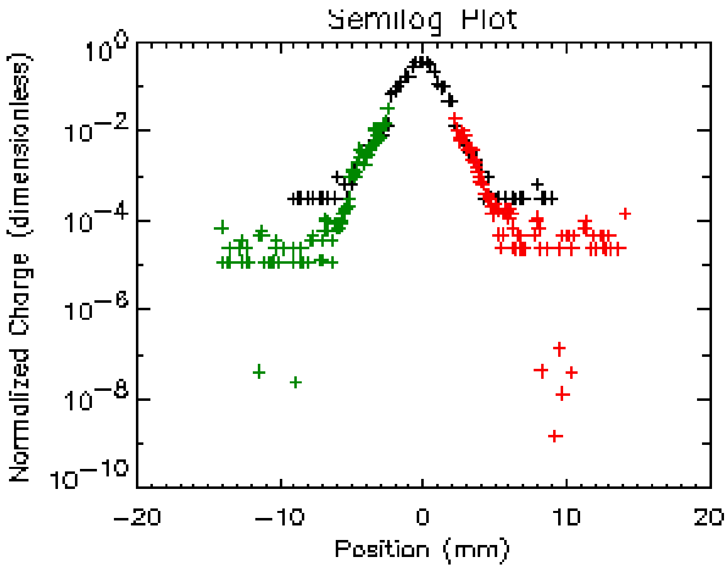

X Axis Beam Profile
scanner 51 75 mA mu=1.5
Wires only
1.0000
0.1000
0.0100
0.0010
0.0001
-10
-5
0
5
10
Position (mm)

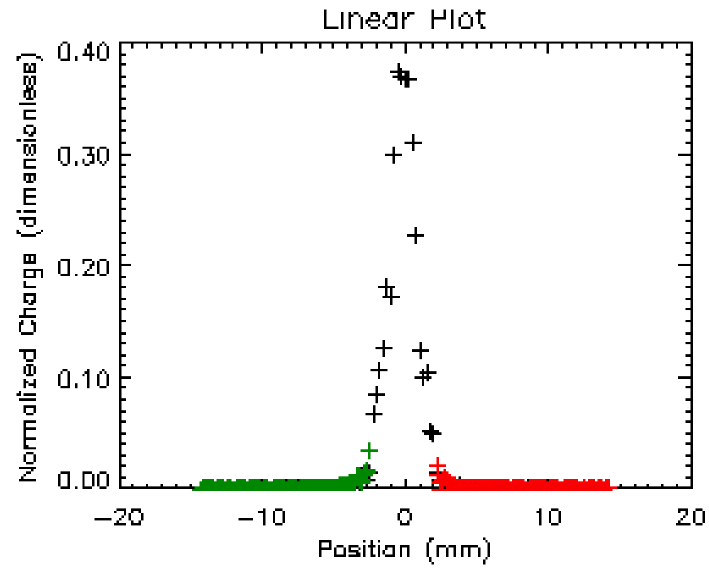

Y Axis Beam Profile
scanner 51-75mA-mu=1.5
Wires only
1.0000
0.1000
0.0100
0.0010
0.0001
-10
-5
0
5
10
Position (mm)

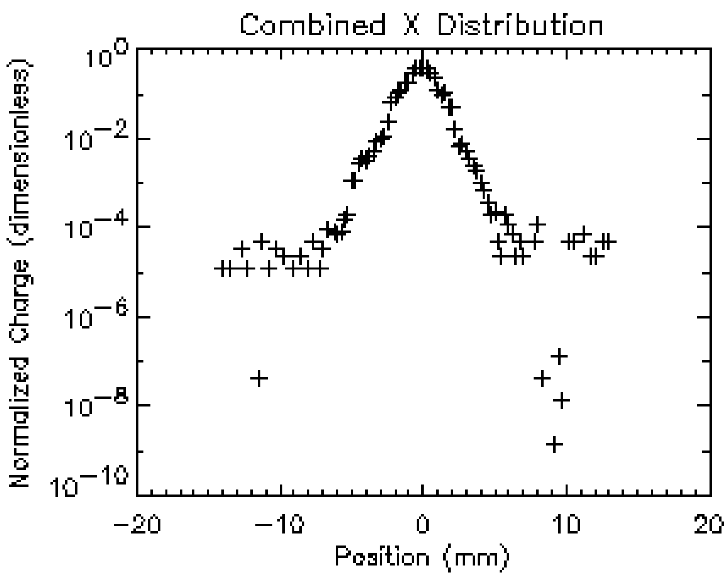
Joining of Wire and Scraper Data

- Scraper data are smoothed and spatially differentiated to transform data to wire-like data.
- Spatial alignment of the data sets is determined from measured relative positions of wire and scrapers.
- Intensity alignment of data is set by overlapping data from the same spatial region.
- We are using a computer automated procedure.

Matched beam-75 mA-scanner 22x







Calculated Moments of the Combined Distribution

File: /u2/aptdvl/wsha_data/2001_May_1_12_03_z22.rws

Mean: −0.18916775 mm

Std Dev: 1.0731855 mm

Skew: −0.027398907

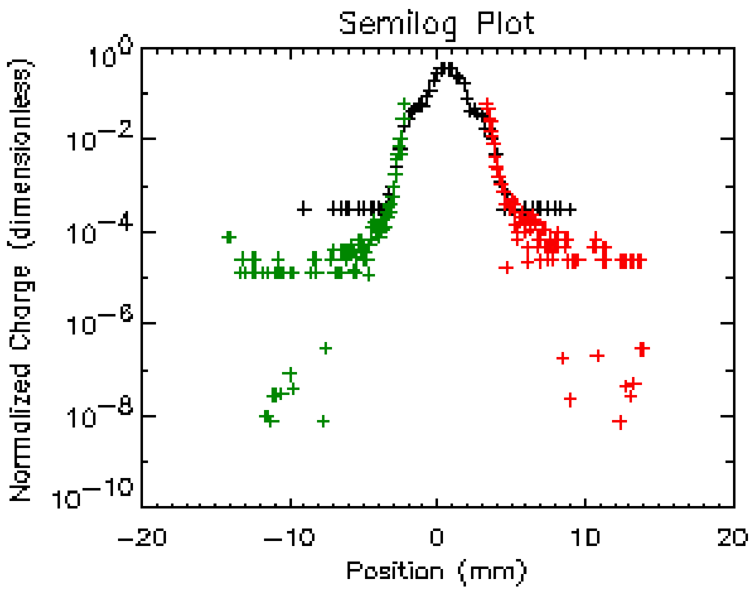
Kurtosis − 2: 0.89974070

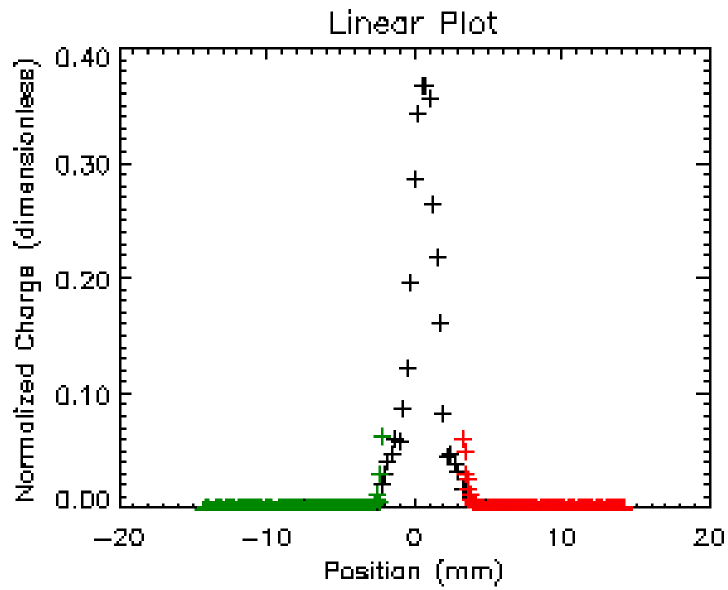
Where Signal to Noise > 2.5

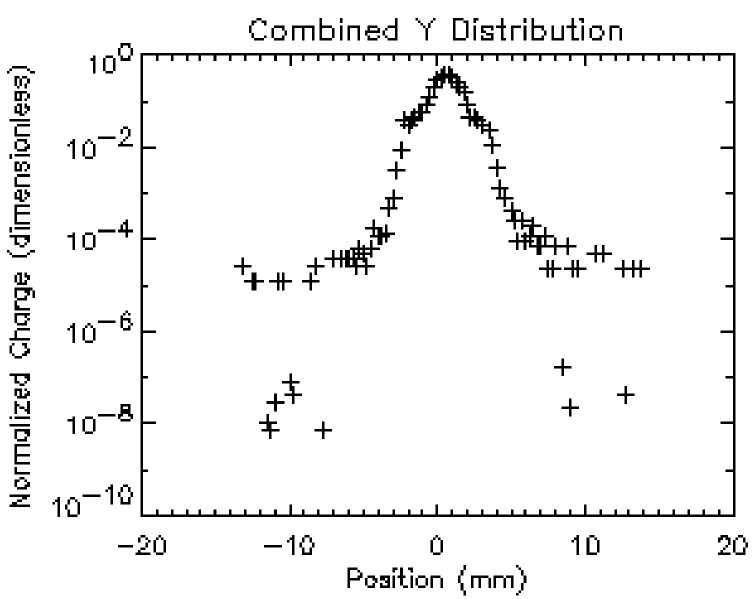
Negative halo scraper −6.08260 mm

Positive halo scraper 6.08470 mm

Matched beam-75 mA-scanner 22y







Calculated Moments of the Combined Distribution

File: /u2/aptdvl/wsha_data/2001_May_1_12_03_z22.rws

Mean: 0.57816085 mm

Std Dev: 1.0635061 mm

Skew: −0.39830483

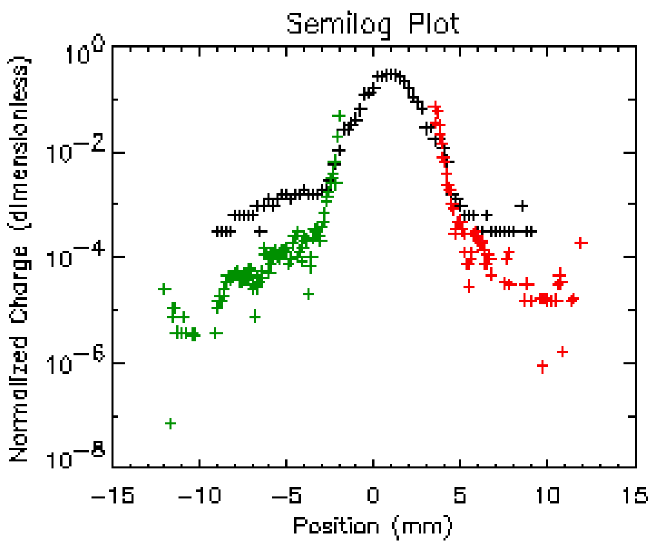
Kurtosis − 2: −3.2343016

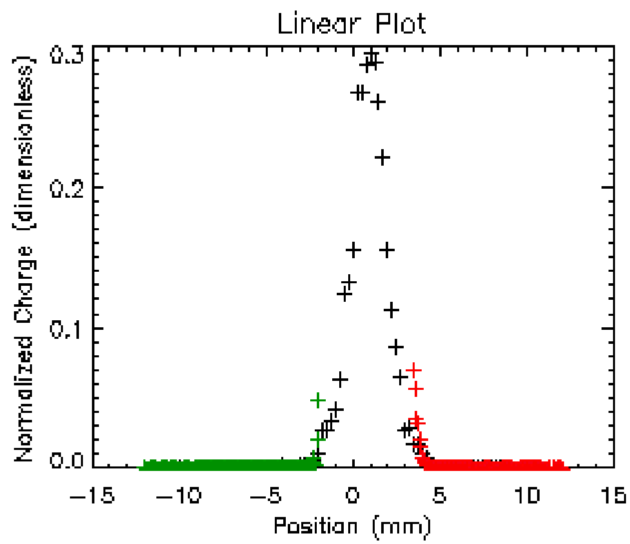
Where Signal to Noise > 2.5

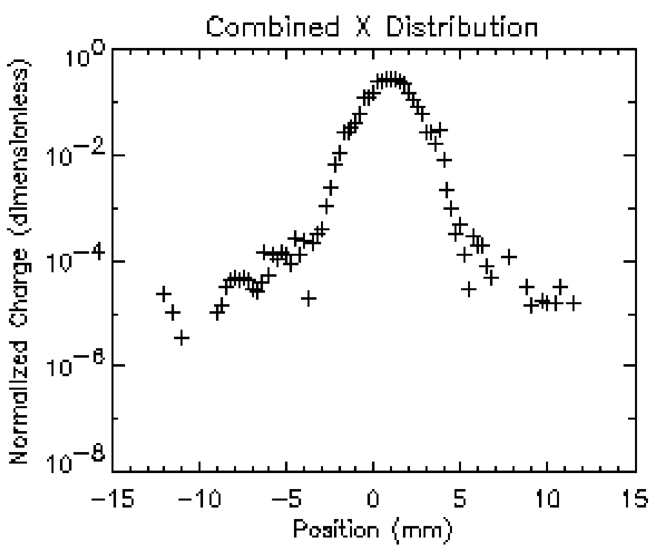
Negative halo scraper −6.40870 mm

Positive halo scraper 7.16340 mm

Matched beam - 75 mA - scanner 51x







Calculated Moments of the Combined Distribution

File: /u2/optdvl/wsha_data/2001_May_2_22_31_z51.rws

Mean: 0.93145387 mm

Std Dev: 1.1019562 mm

Skew: −0.22773781

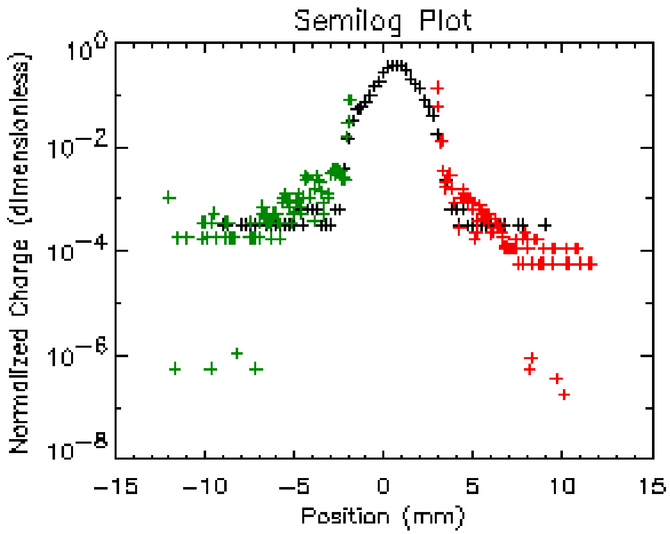
Kurtosis − 2: 1.3098605

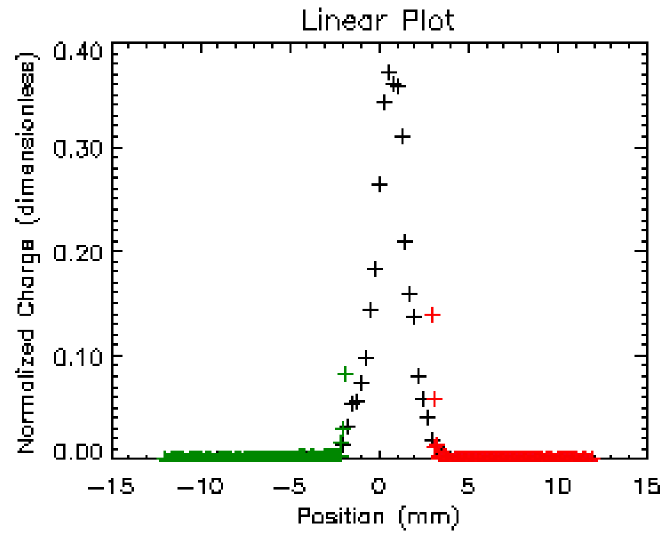
Where Signal to Noise > 2.5

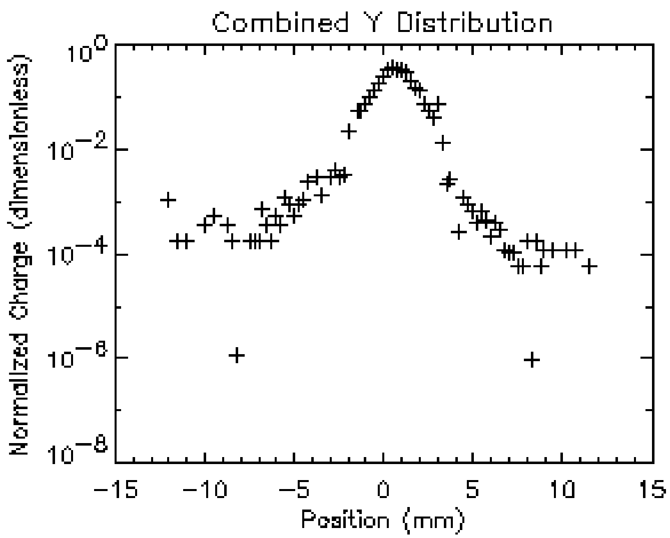
Negative halo scraper −8.32410 mm

Positive halo scraper 5.82570 mm

Matched beam 75 mA scanner 51y







Calculated Moments of the Combined Distribution

File: /u2/aptdvl/wsha_data/2001_May_3_17_53_z22.rwa

Mean: 0.69343749 mm

Std Dev: 1.0983191 mm

Skew: −0.76466297

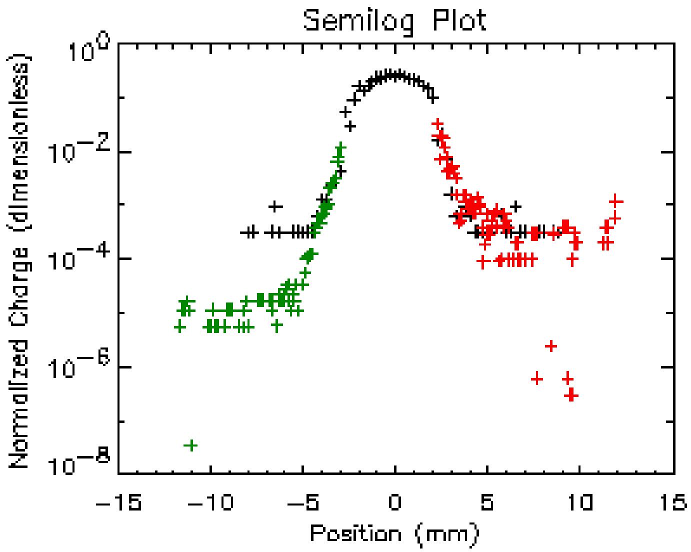
Kurtosis − 2: 8.9605916

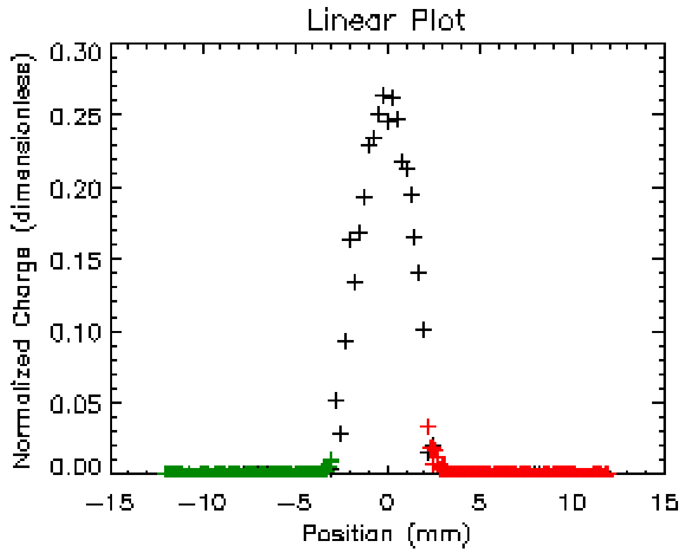
Where Signal to Noise > 2.5

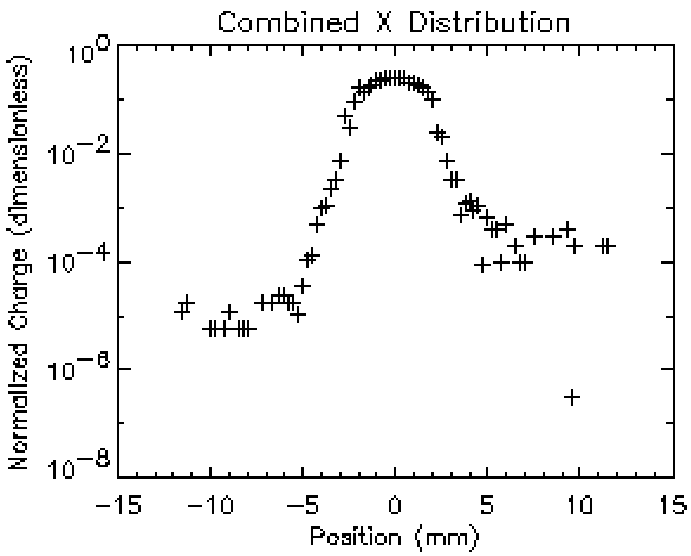
Negative halo scraper −6.74990 mm

Positive halo scraper 7.82430 mm

Mismatched beam (mu=1.5)-75 mA-scanner 22x







Calculated Moments of the Combined Distribution

File: /u2/aptdvl/wsha_data/2001_May_3_17_53_z22.rws

Mean: −0.13342924 mm

Std Dev: 1.1961941 mm

Skew: −1.0090963

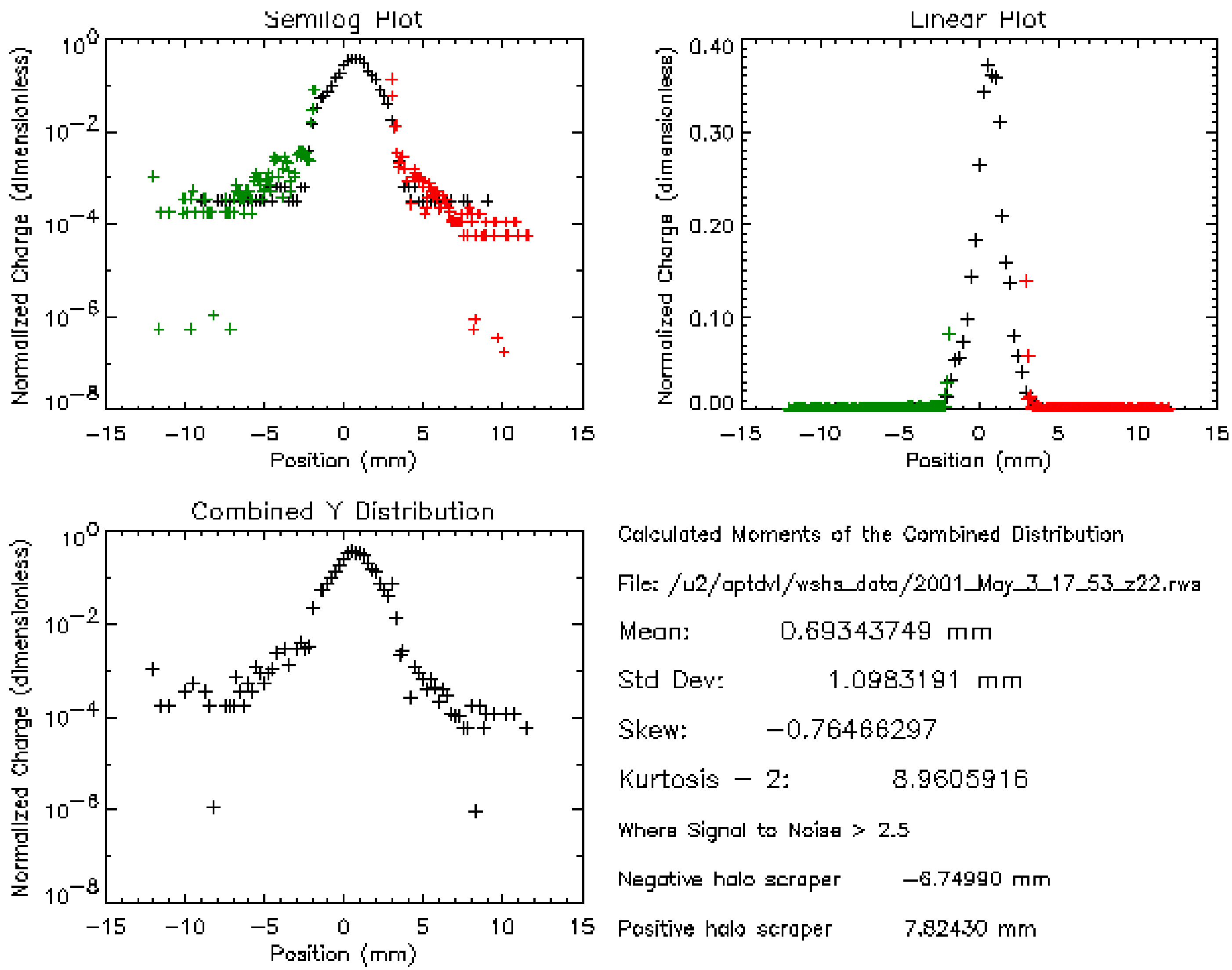
Kurtosis − 2: −9.5550296

Where Signal to Noise > 2.5

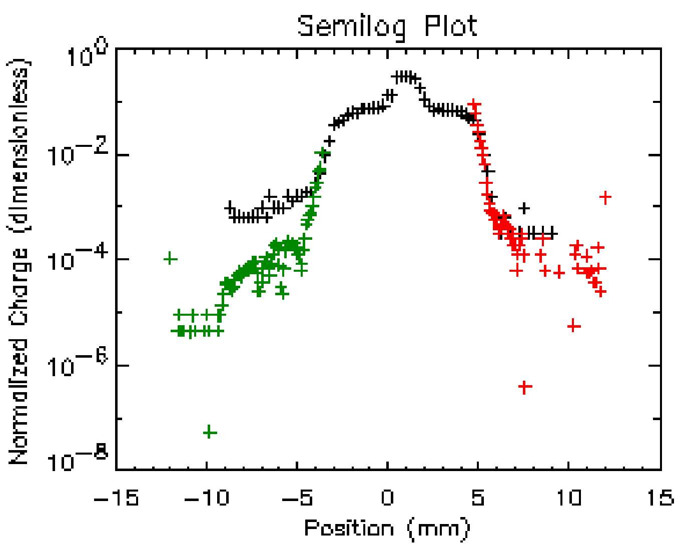
Negative halo scraper −5.82760 mm

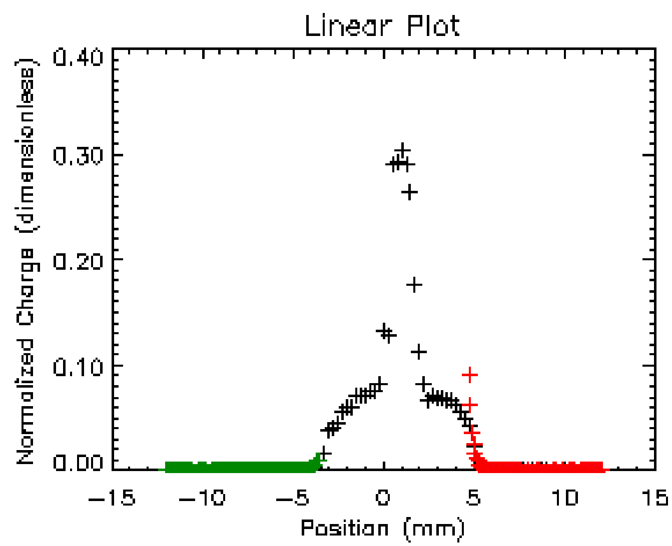
Positive halo scraper 5.83330 mm

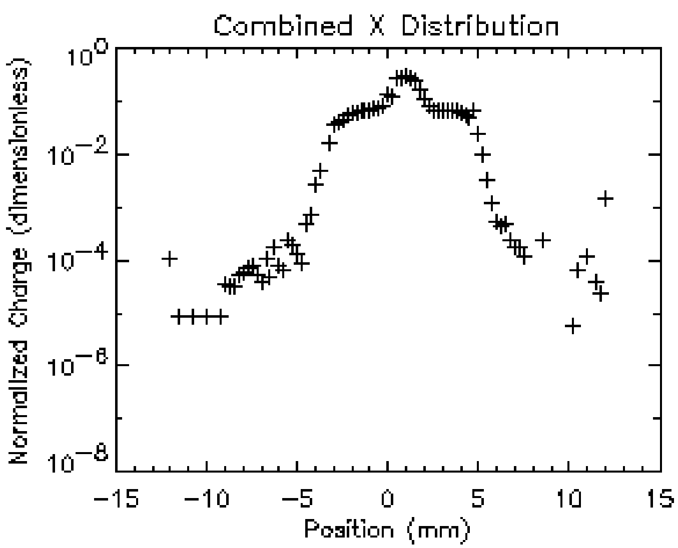
Mismatched beam (mu=1.5)-75 mA-scanner 22y



Mismatched beam (mu=1.5)-75 mA-scanner 51x







Calculated Moments of the Combined Distribution

File: /u2/aptdvl/wsha_data/2001_May_3_21_34_z51.rws

Mean: 1.0051845 mm

Std Dev: 1.8190567 mm

Skew: 0.039269982

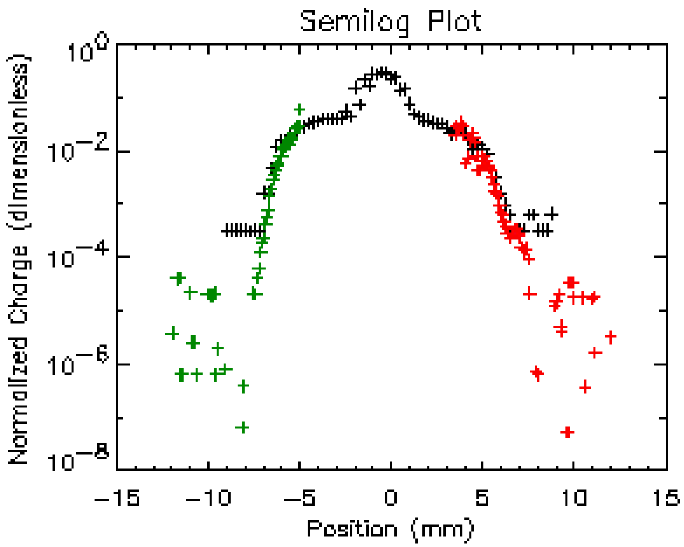
Kurtosis − 2: 1.5899716

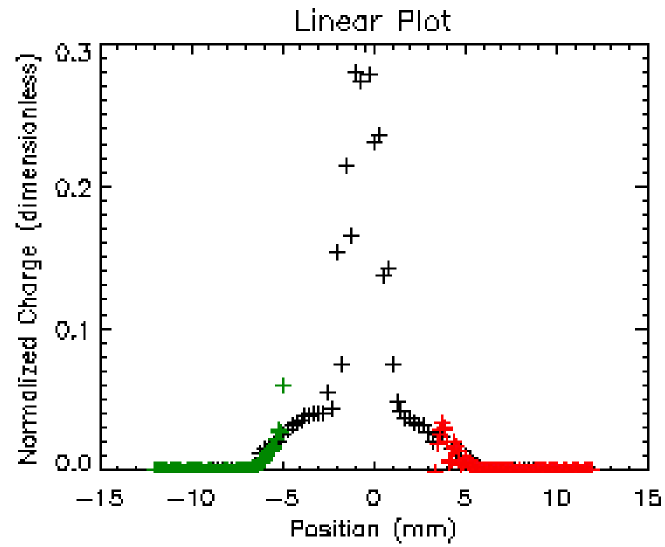
Where Signal to Noise > 2.5

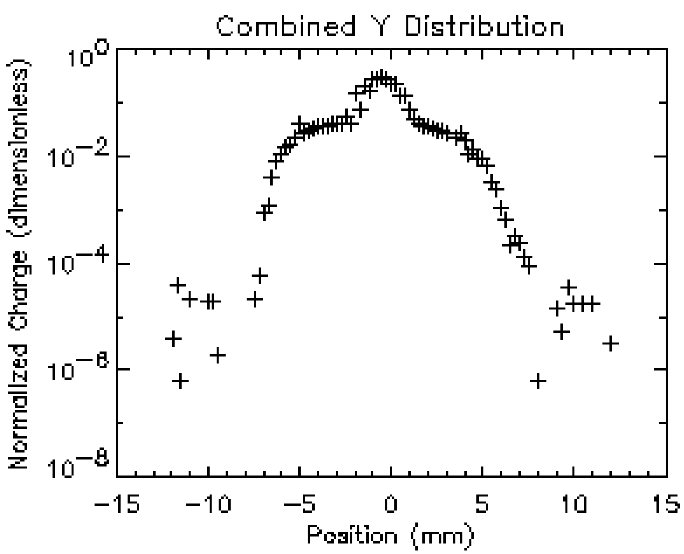
Negative halo scraper −8.33130 mm

Positive halo scraper 5.91190 mm

Mismatched beam (mu=1.5)-75 mA-scanner 51y







Calculated Moments of the Combined Distribution

File: /u2/aptdvl/wsha_data/2001_May_3_21_34_z51.rwa

Mean: −0.69452590 mm

Std Dev: 1.9176993 mm

Skew: −0.084216054

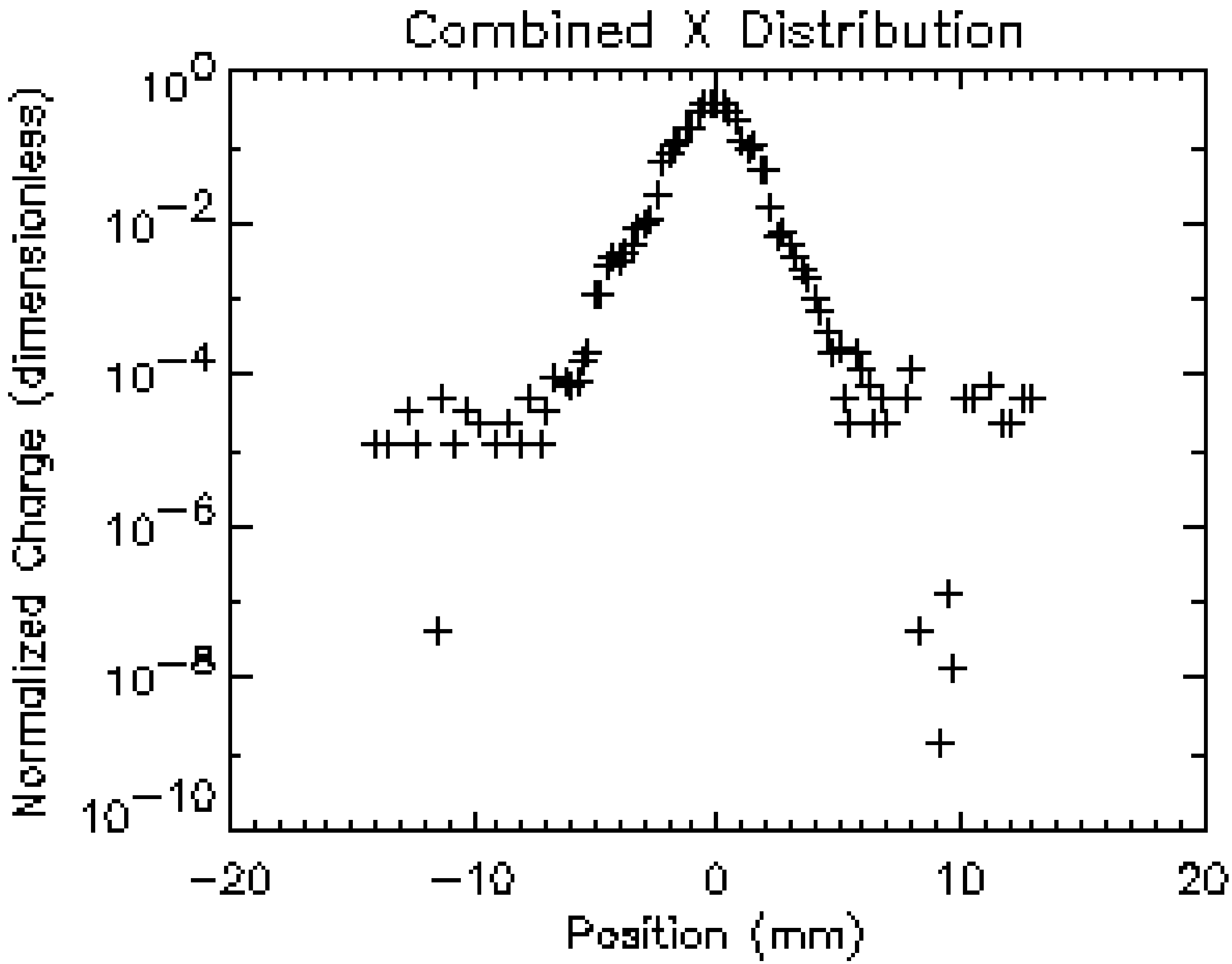
Kurtosis − 2: 2.3120407

Where Signal to Noise > 2.5

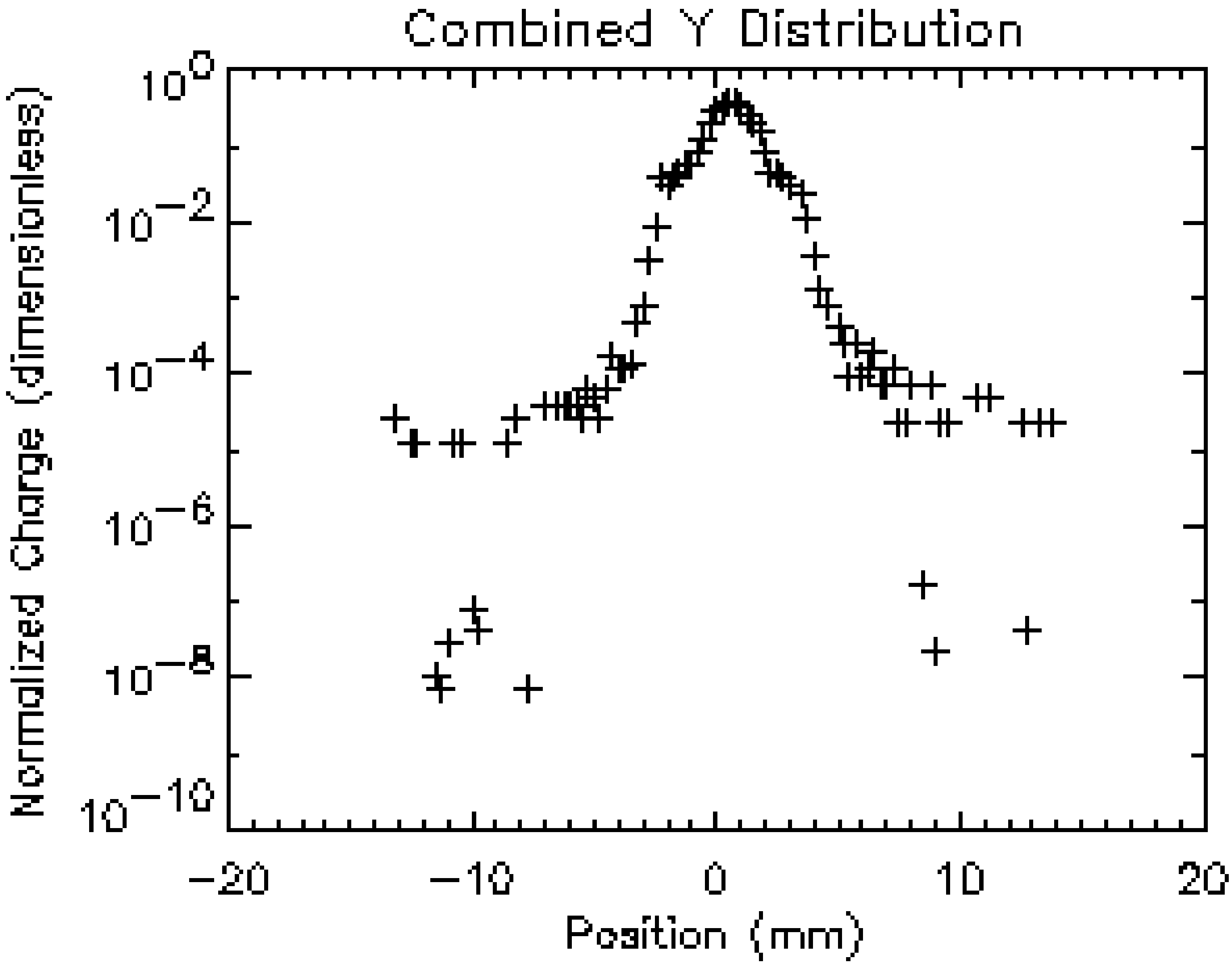
Negative halo scraper −6.65410 mm

Positive halo scraper 6.74560 mm

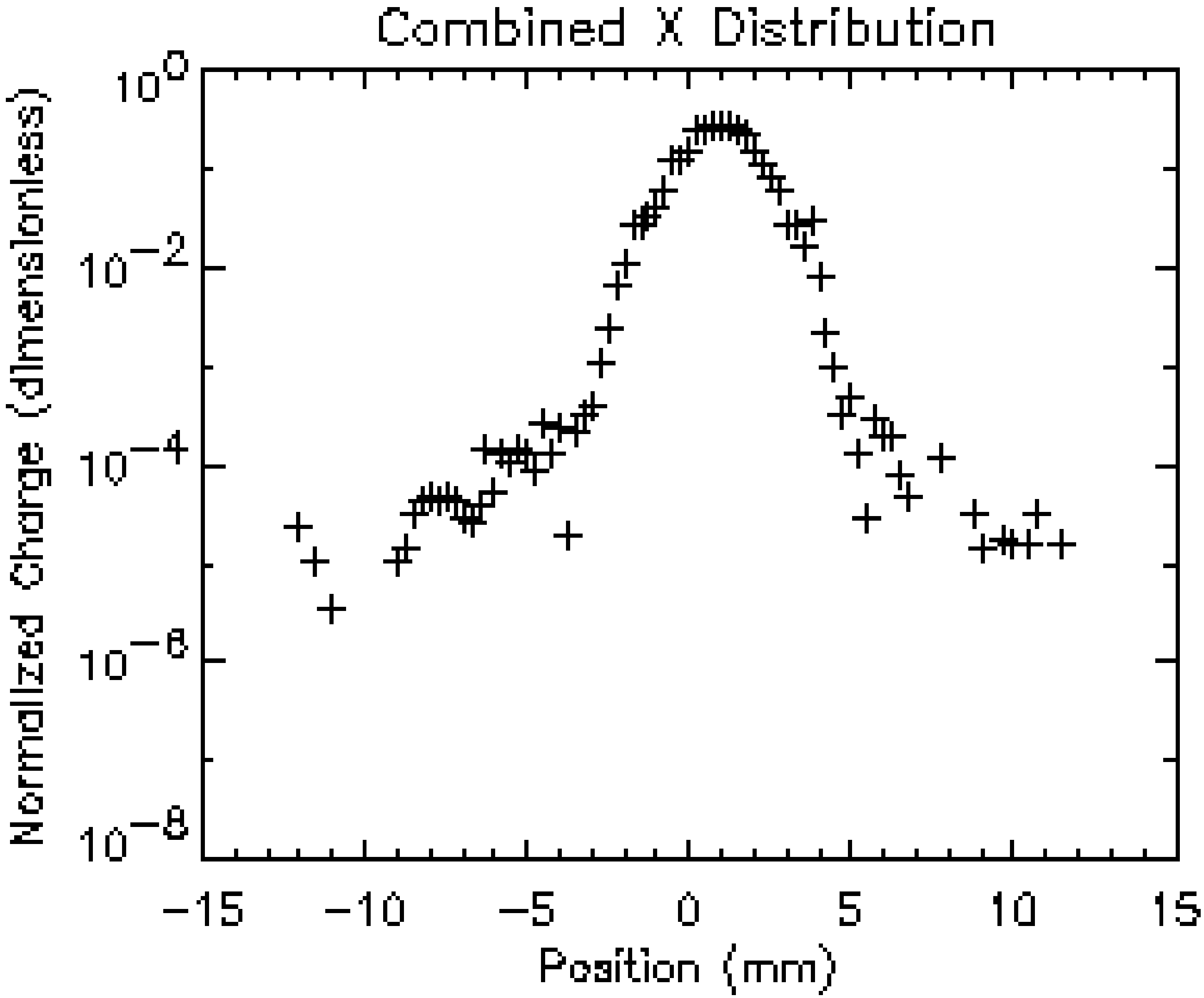
Matched beam-75 mA-scanner 22x



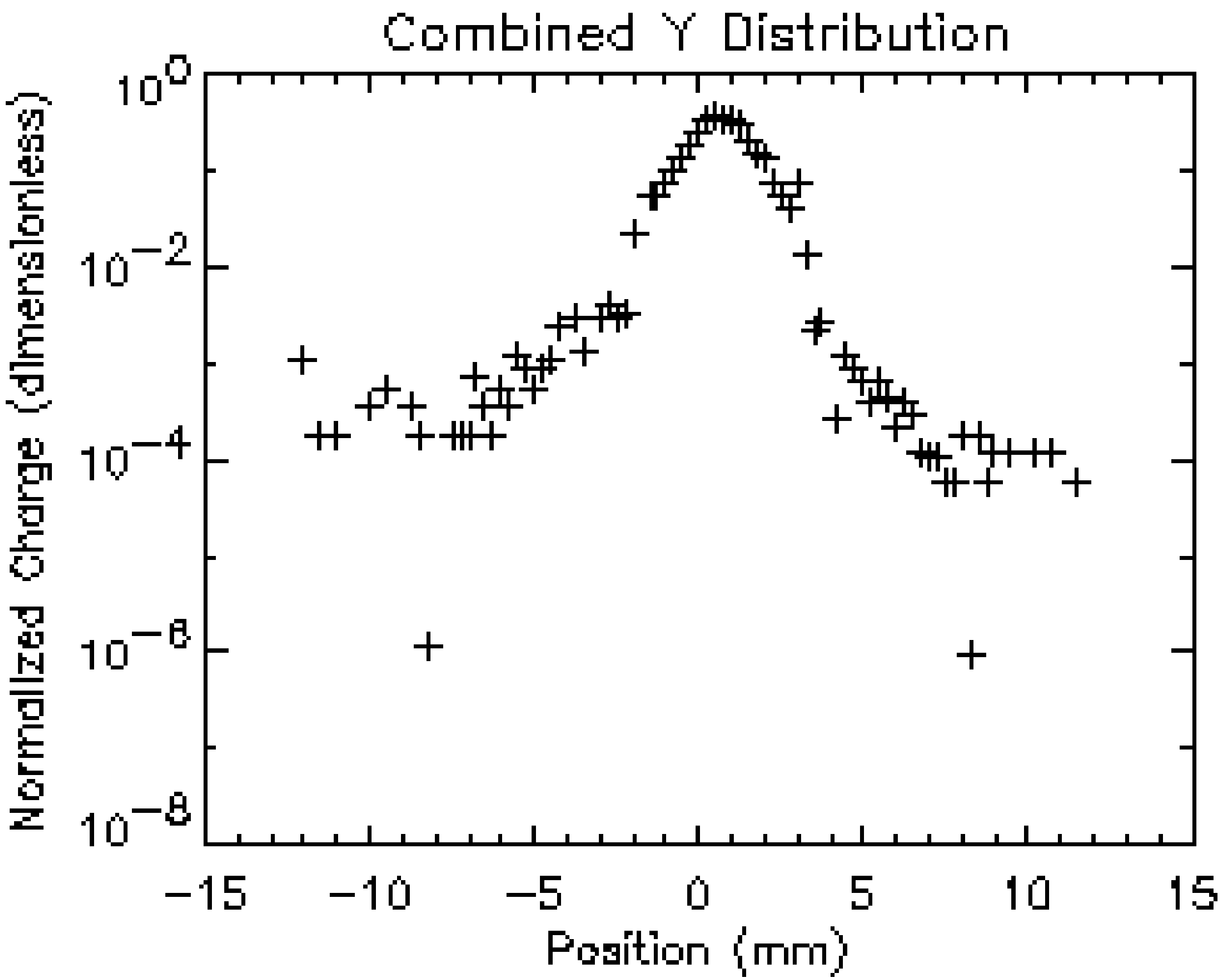
Matched beam-75 mA-scanner 22y



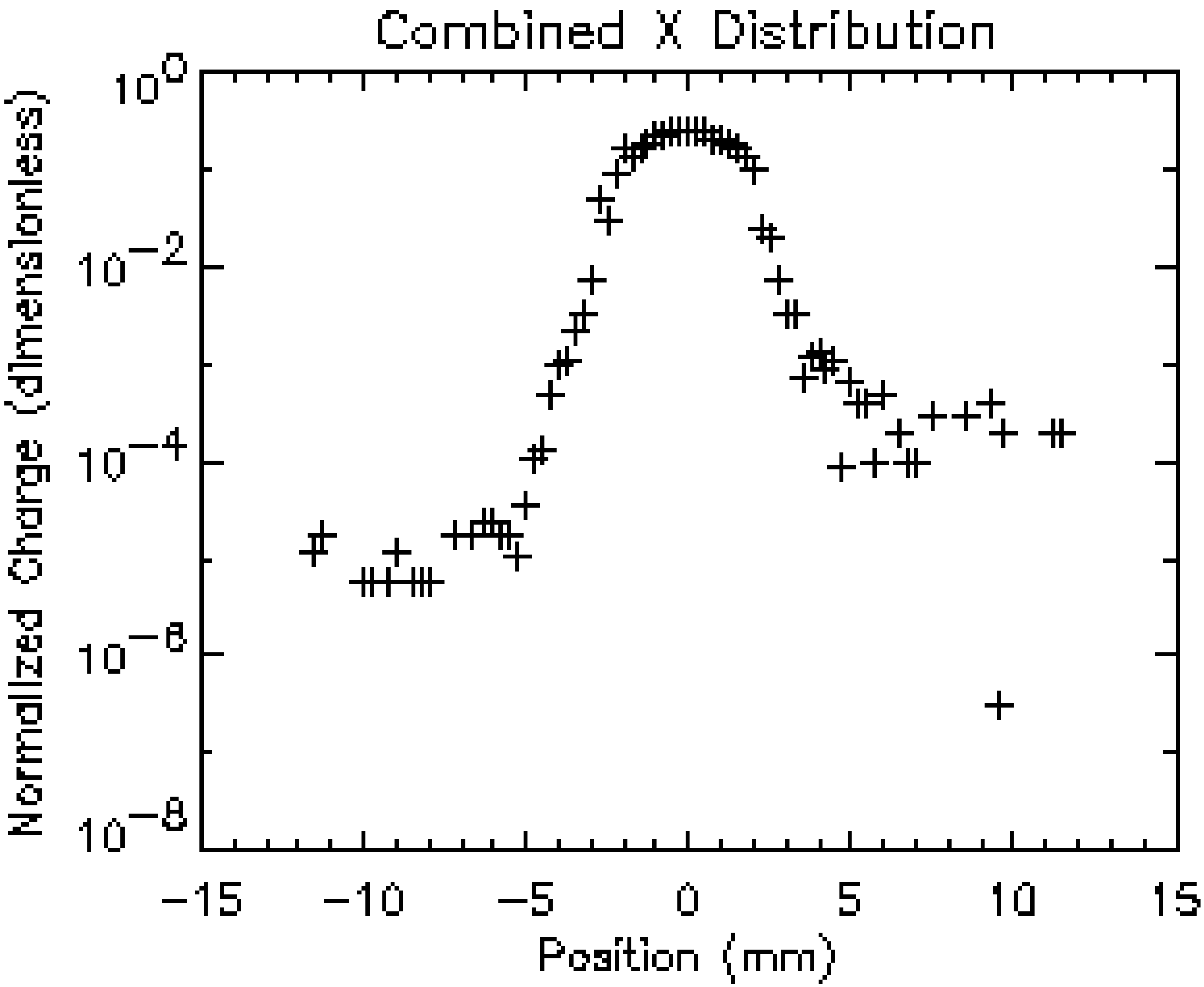
Matched beam - 75 mA - scanner 51x



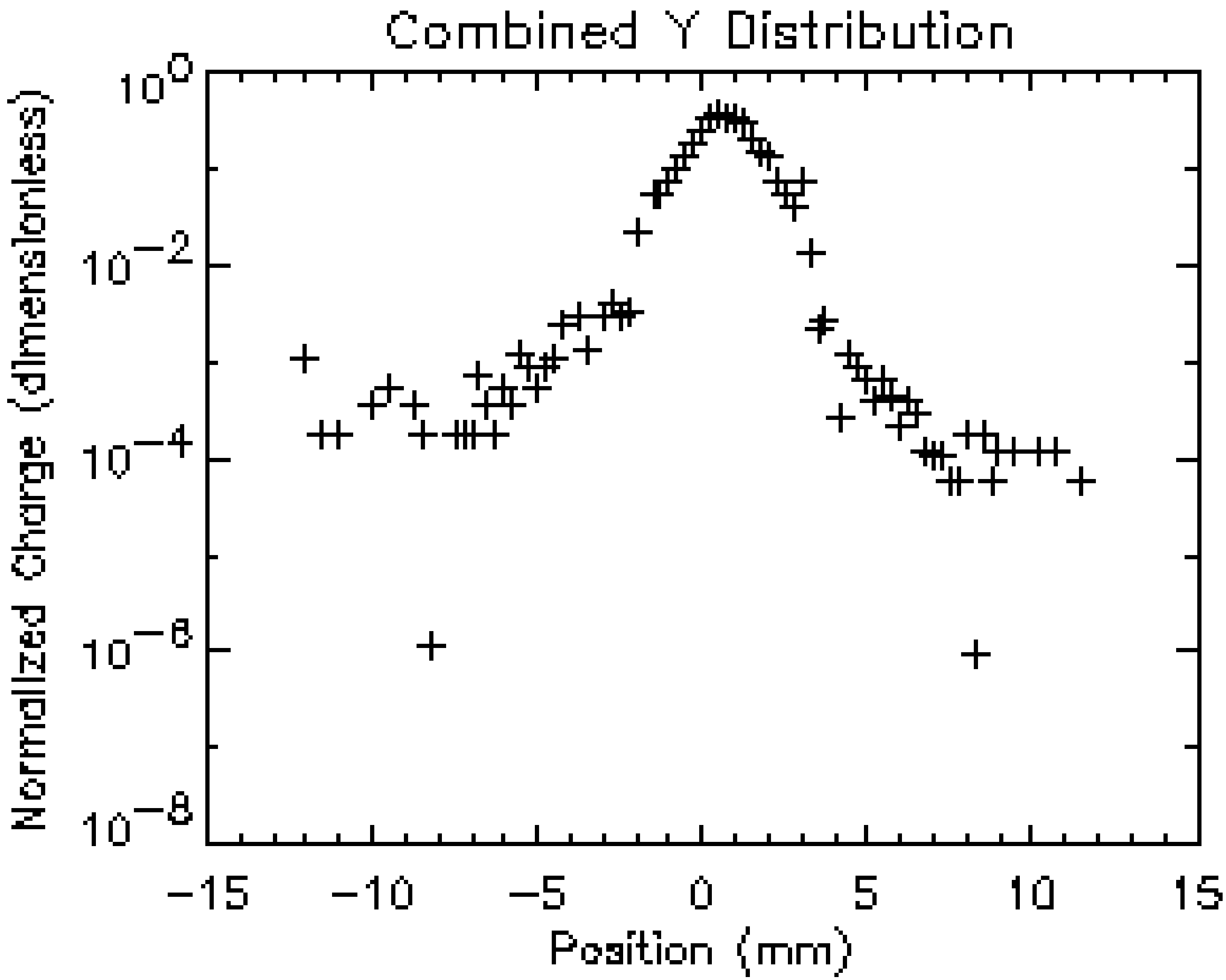
Matched beam 75 mA scanner 51y



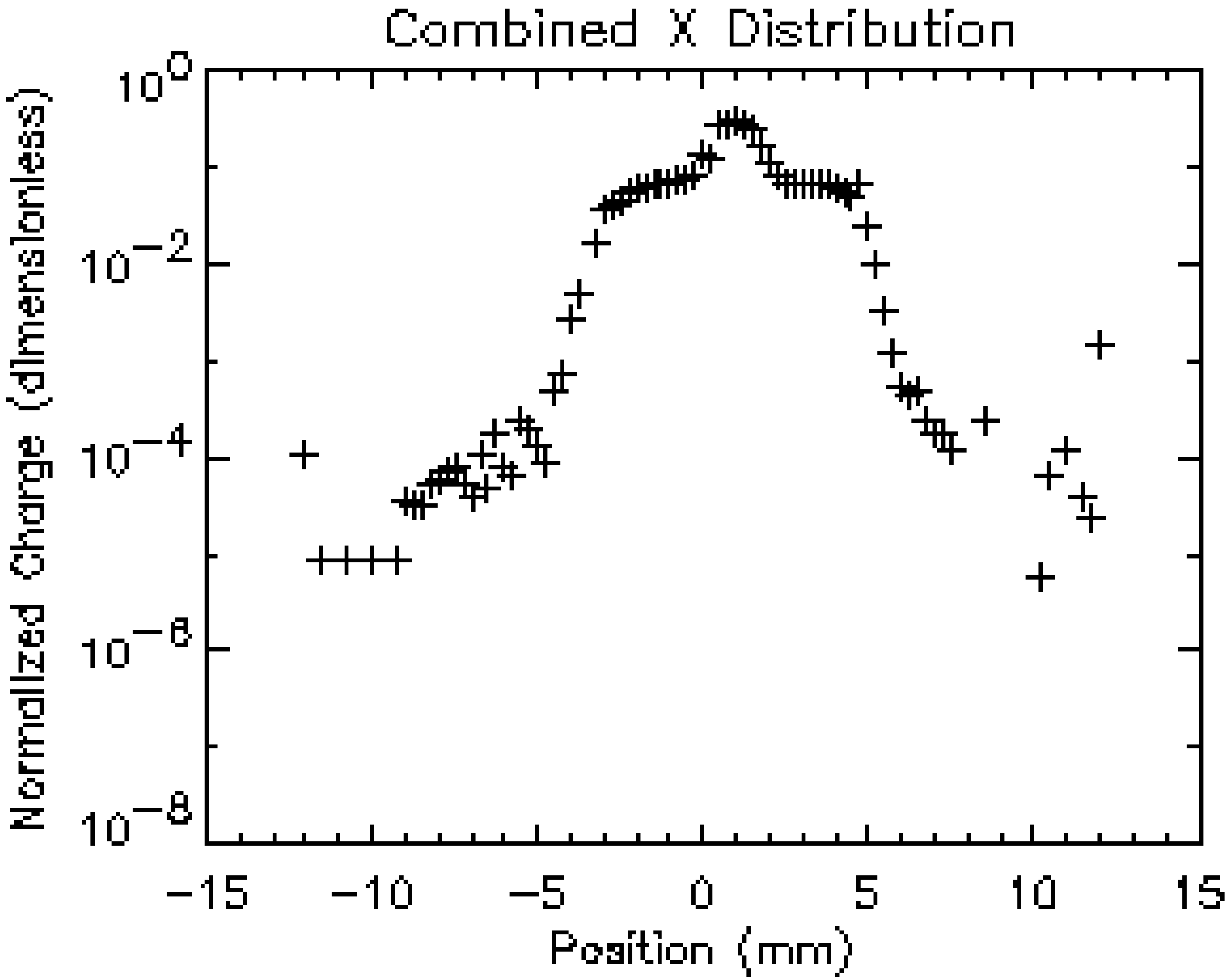
Mismatched beam (mu=1.5)-75 mA-scanner 22x



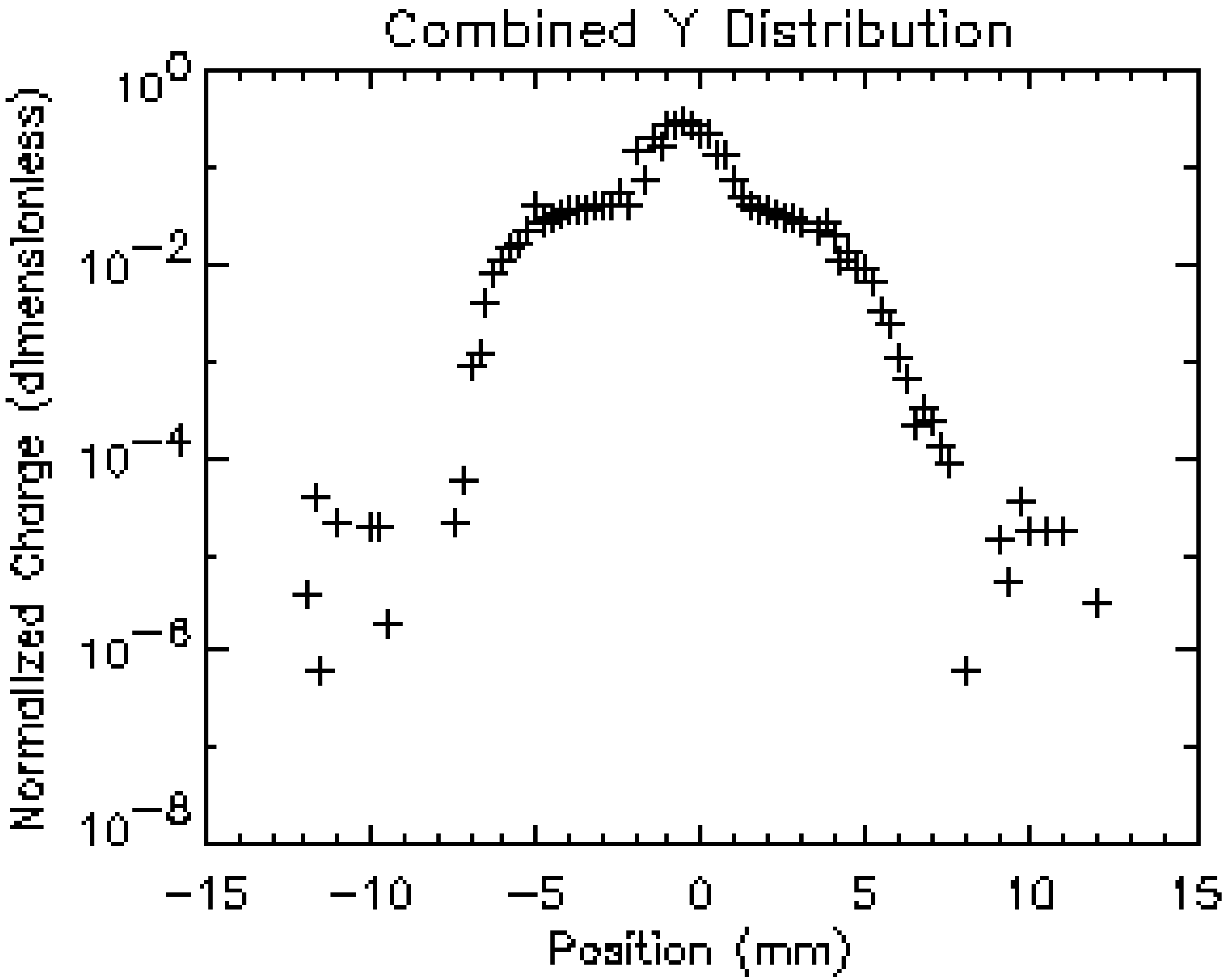
Mismatched beam (mu=1.5)-75 mA-scanner 22y

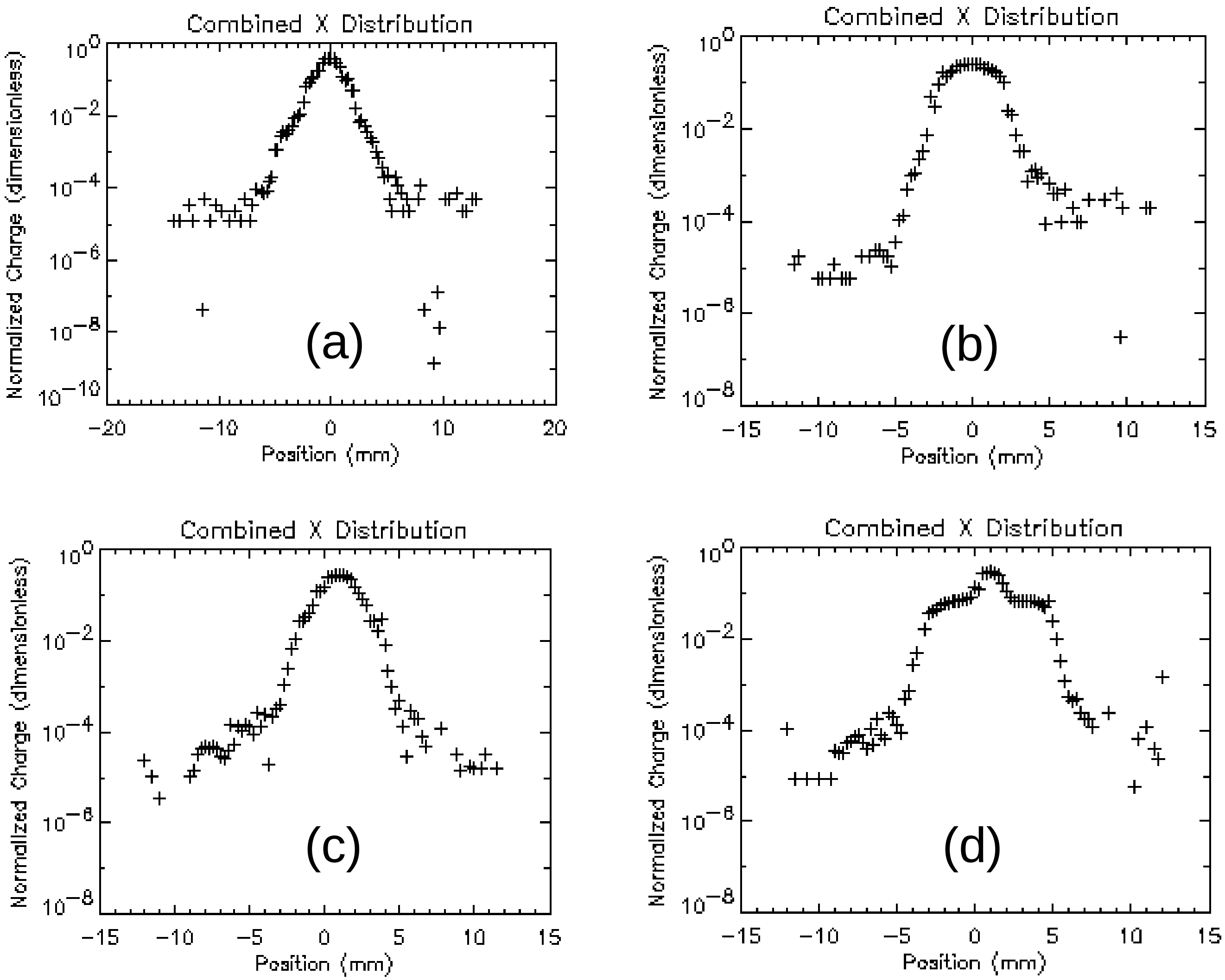


Mismatched beam (mu=1.5)-75 mA-scanner 51x

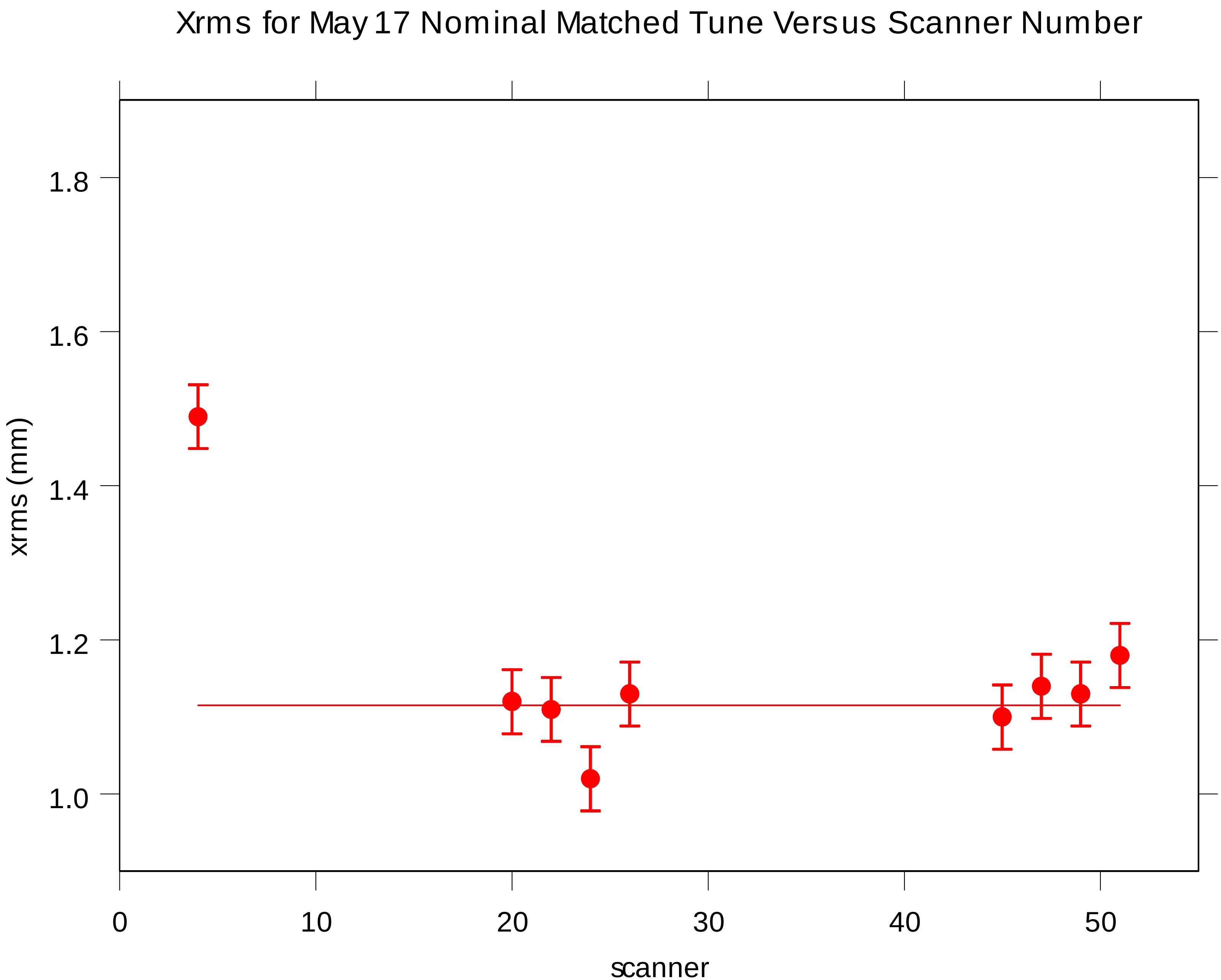


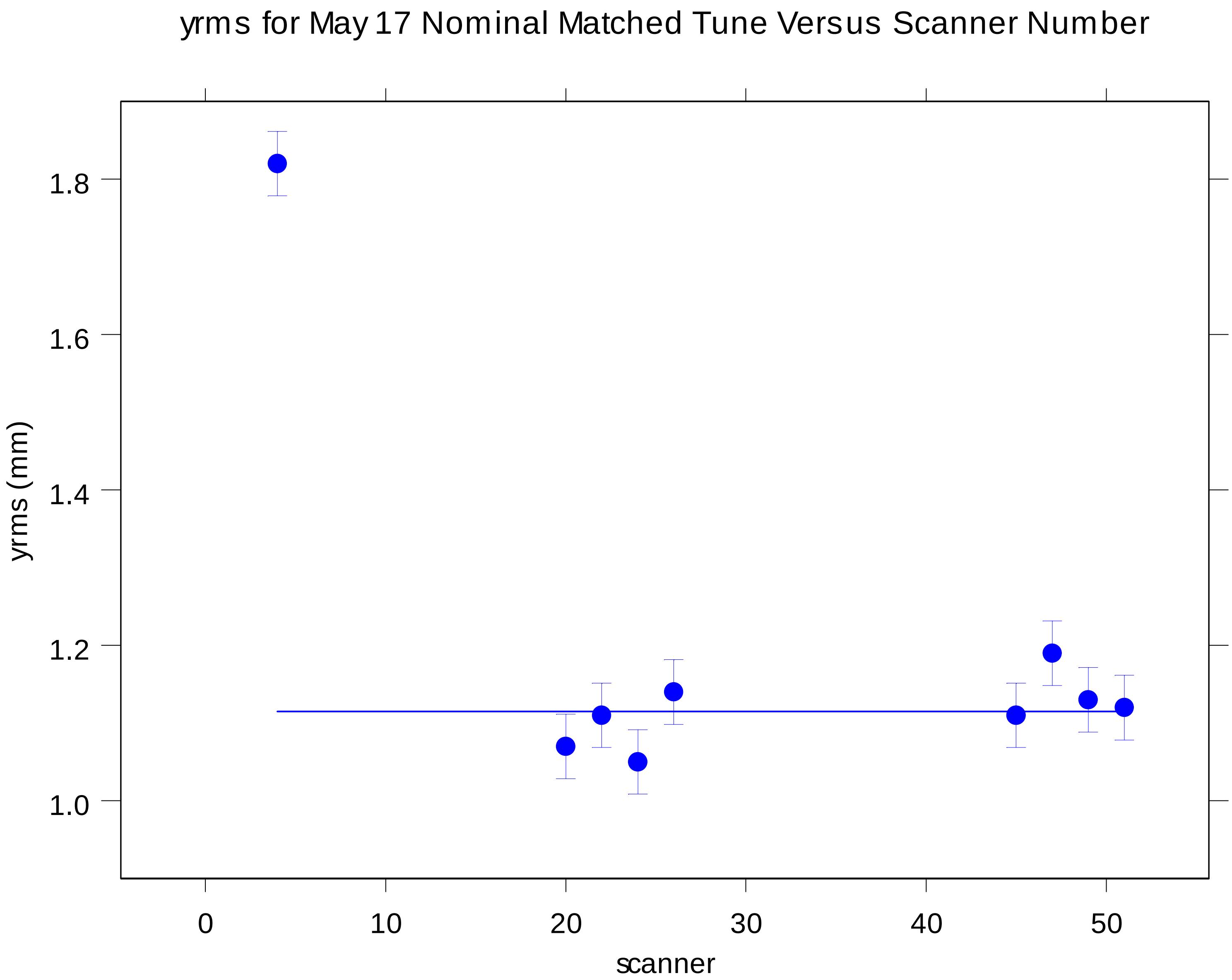
Mismatched beam (mu=1.5)-75 mA-scanner 51y



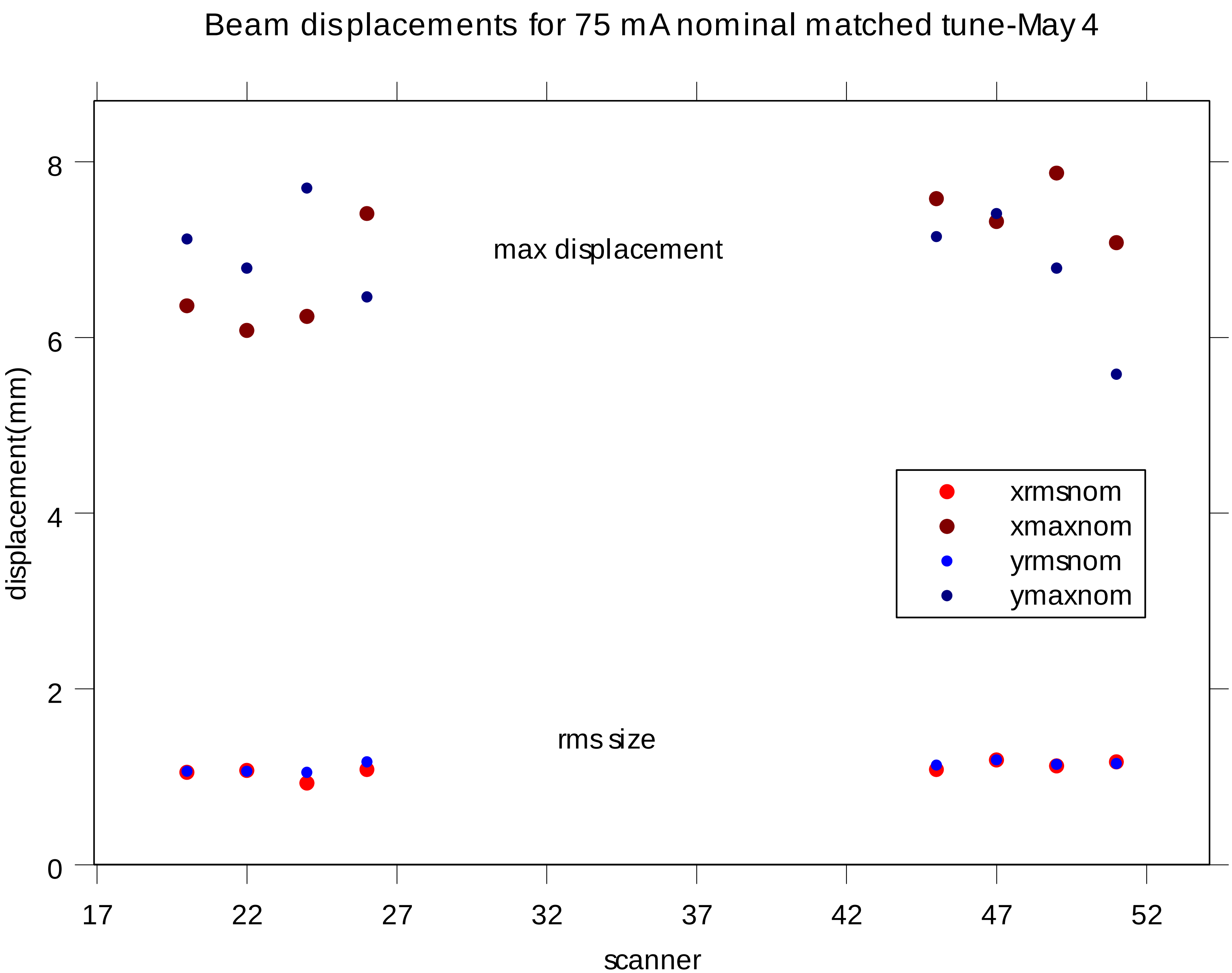


Combined X Distribution
Normalized Charge (dimensionless)
Position (mm)
(a)
(b)
(c)
(d)

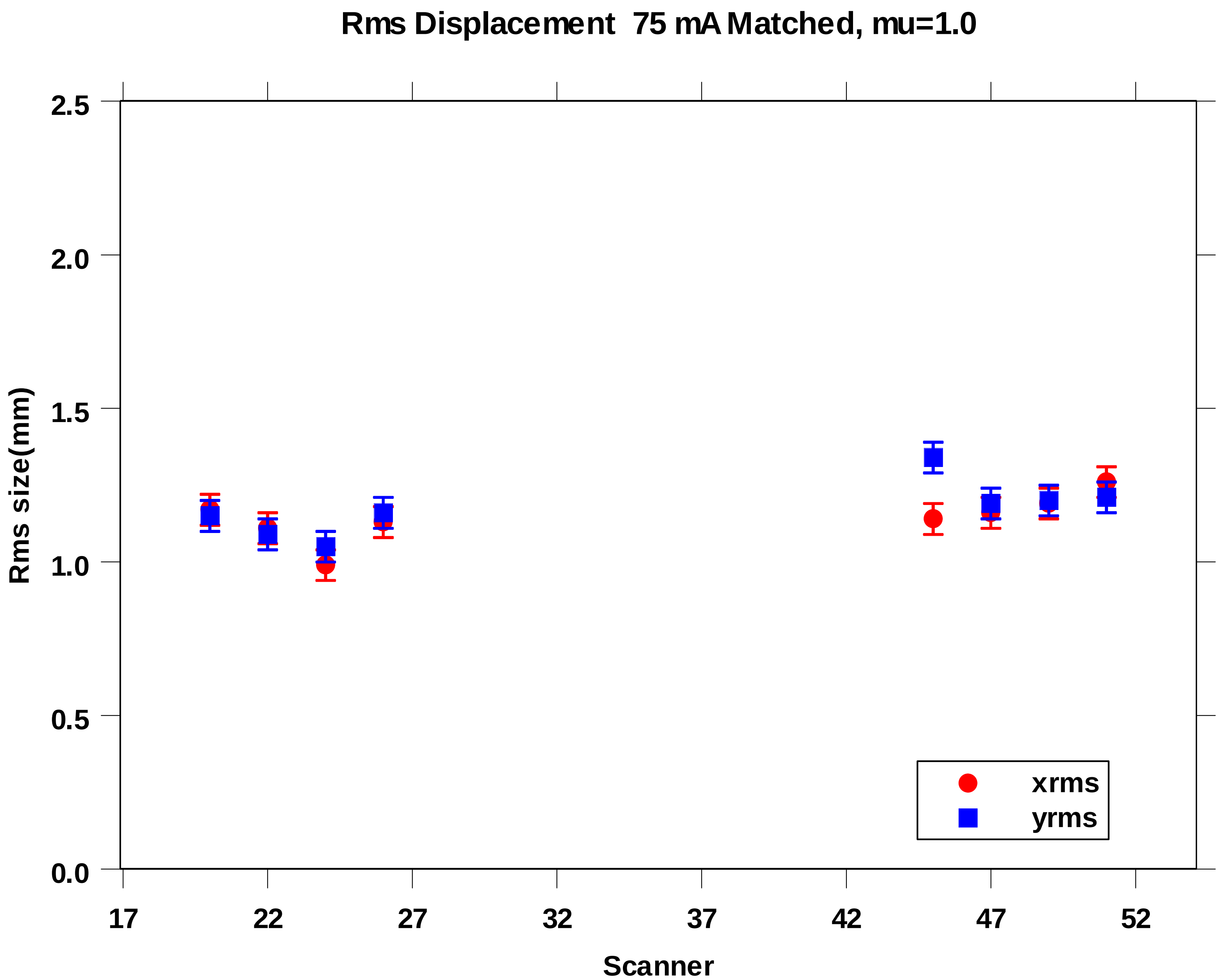

Xrms for May 17 Nominal Matched Tune Versus Scanner Number
xrms (mm)
1.8
1.6
1.4
1.2
1.0
0
10
20
30
40
50
scanner

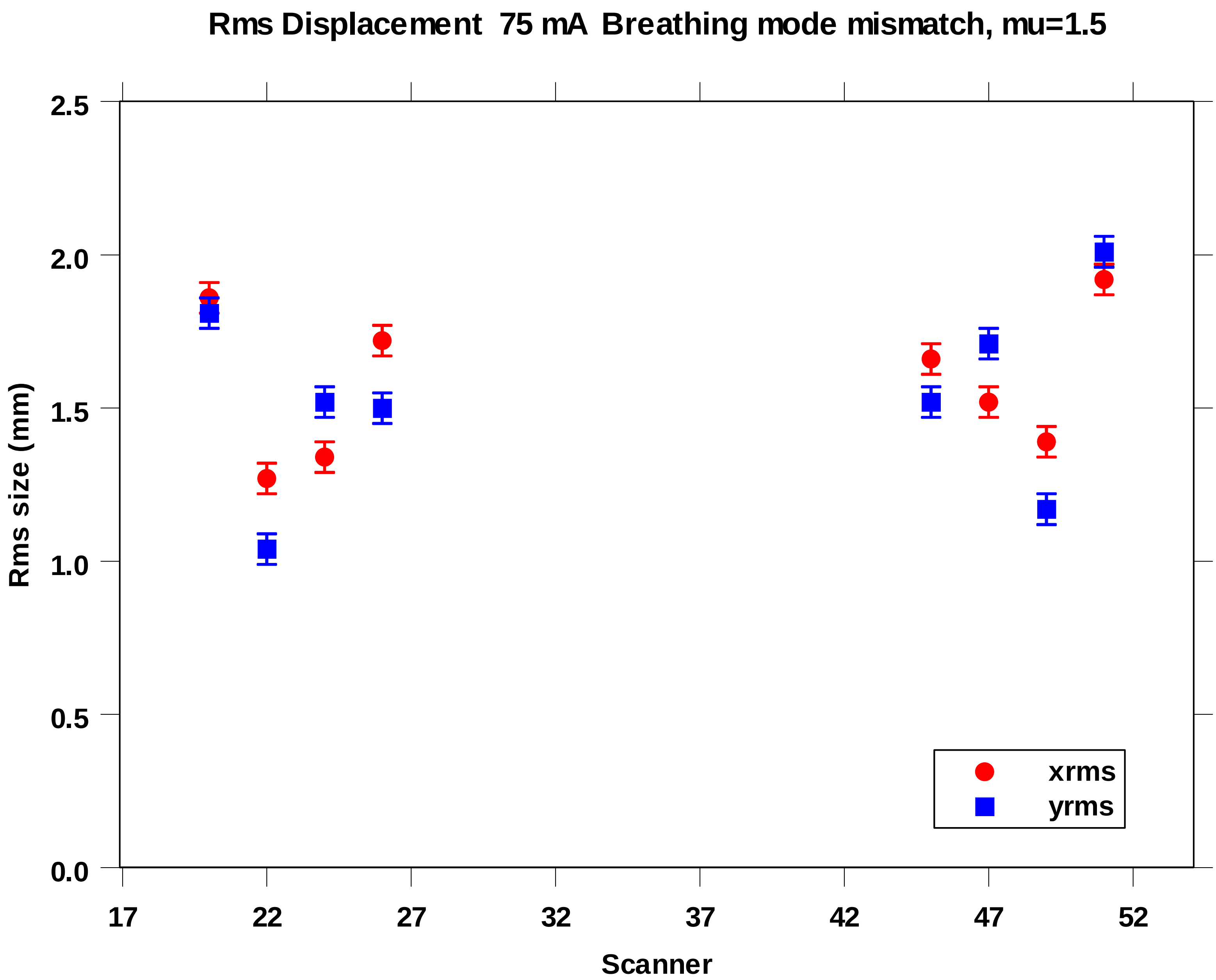


yrms for May 17 Nominal Matched Tune Versus Scanner Number
yrms (mm)
1.0
1.2
1.4
1.6
1.8
0
10
20
30
40
50
scanner

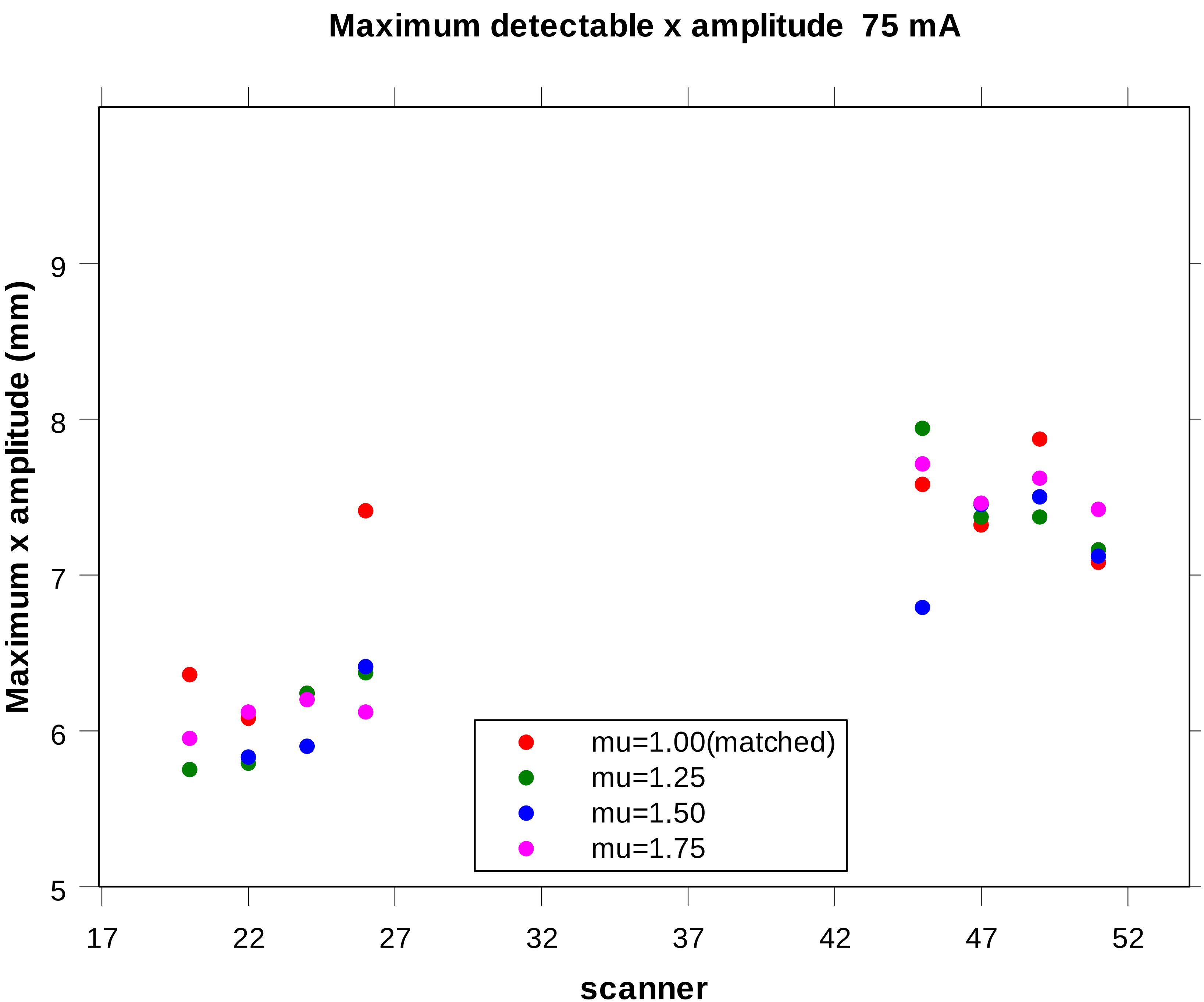


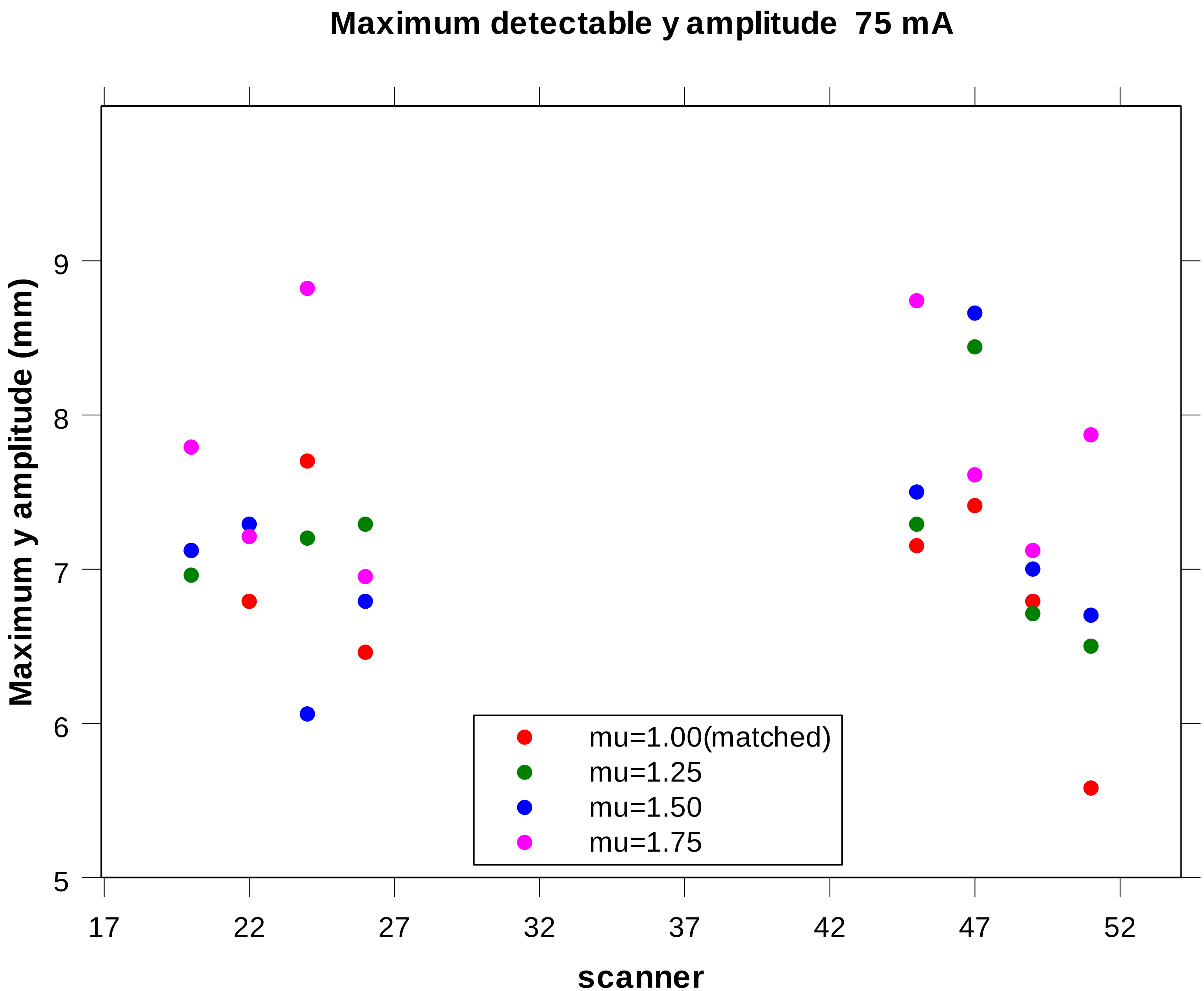
Beam displacements for 75 mA nominal matched tune-May 4
max displacement
rms size
xrmsnom
xmaxnom
yrmsnom
ymaxnom
displacement(mm)
0
2
4
6
8
17
22
27
32
37
42
47
52
scanner

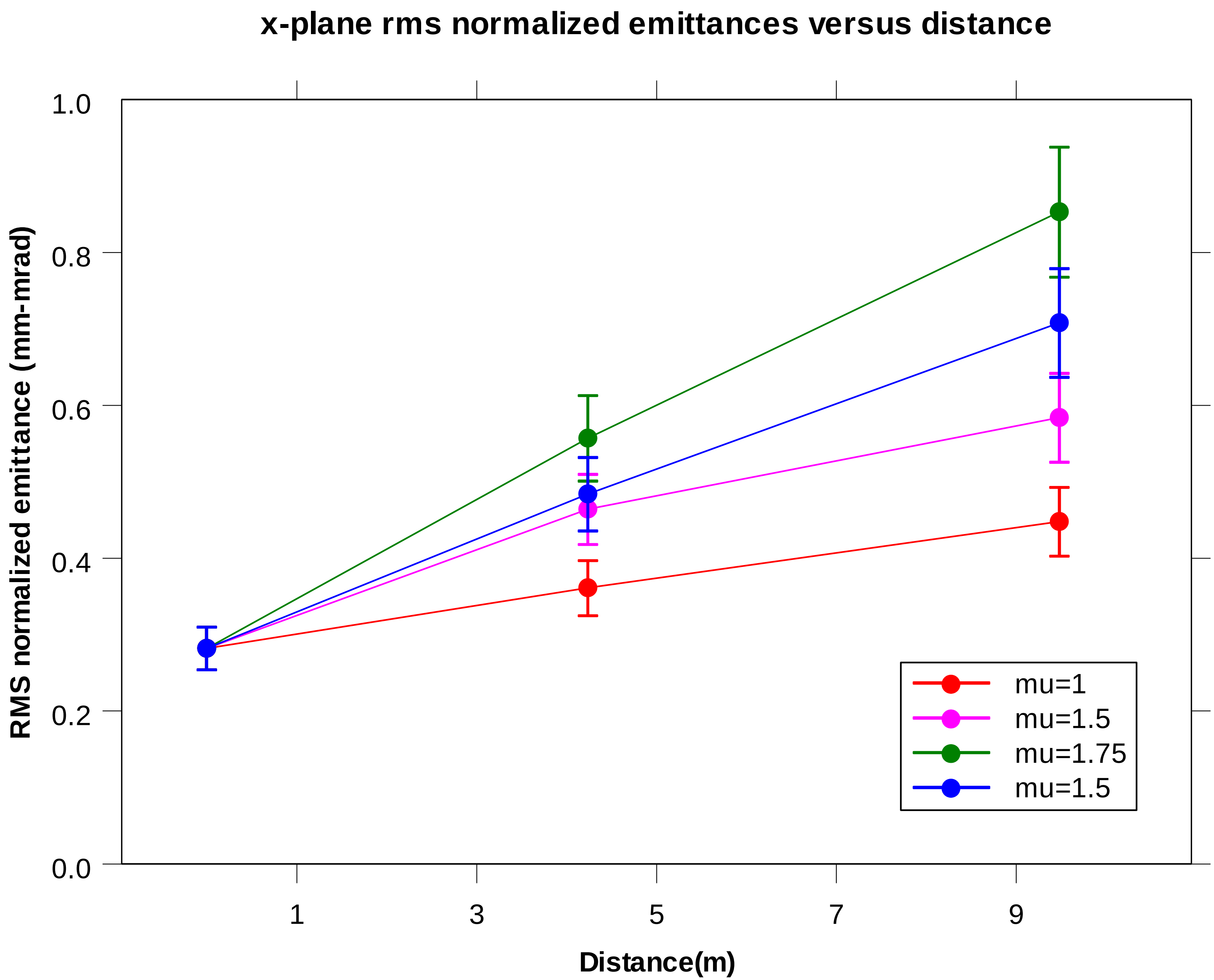

Rms Displacement 75 mA Matched, mu=1.0
Rms size(mm)
2.5
2.0
1.5
1.0
0.5
0.0
17
22
27
32
37
42
47
52
Scanner
xrms
yrms

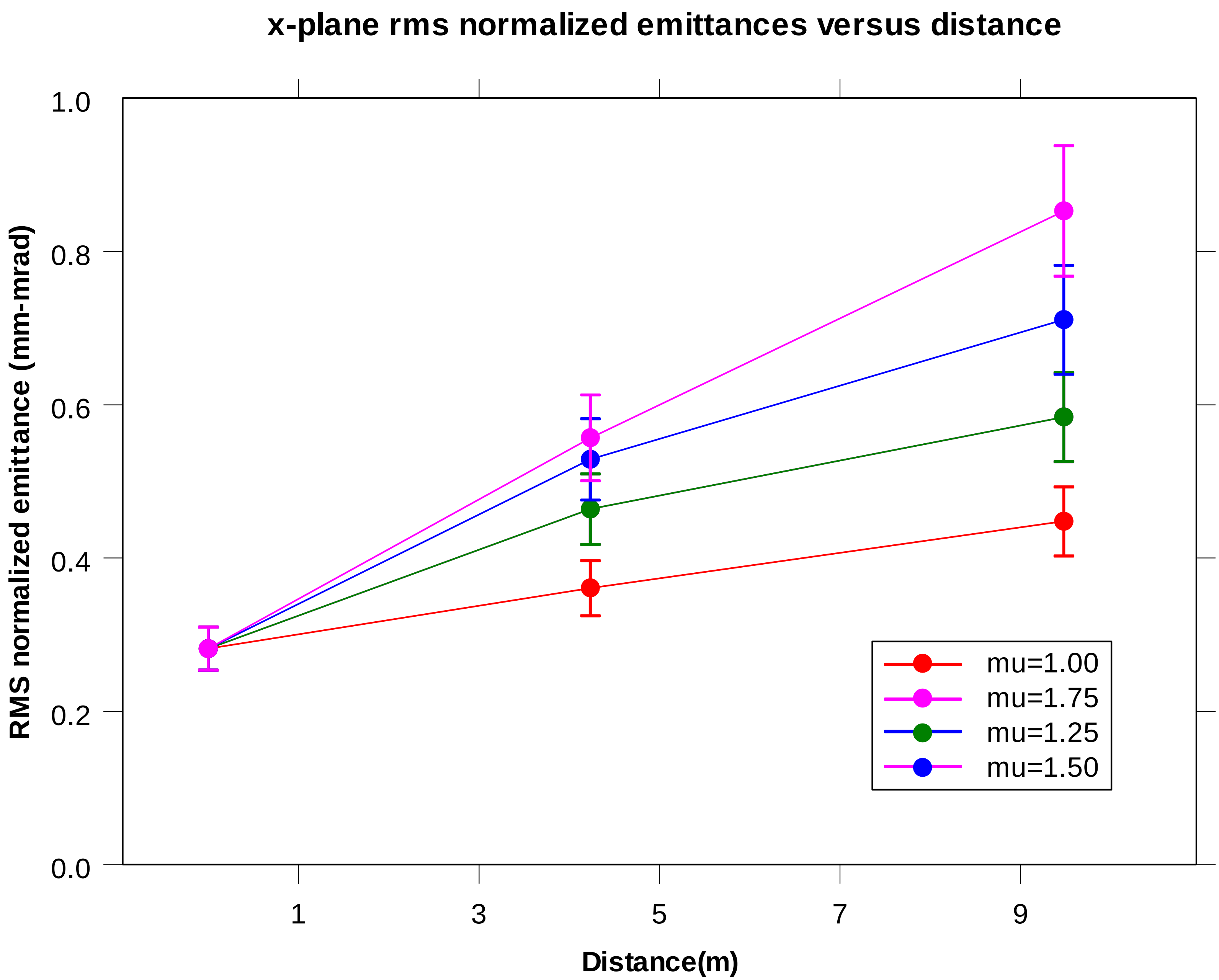


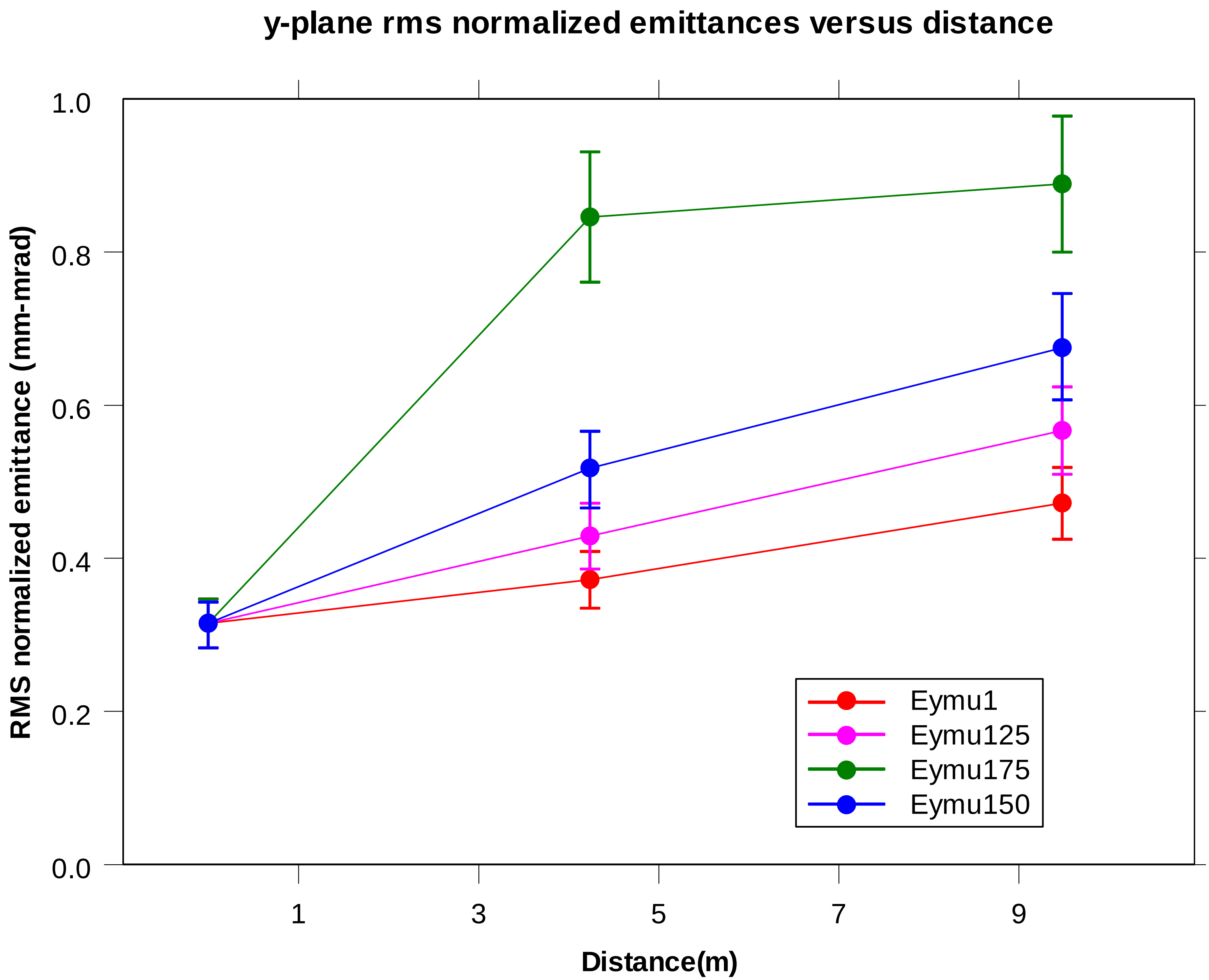
Rms Displacement 75 mA Breathing mode mismatch, mu=1.5
2.5
2.0
1.5
1.0
0.5
0.0
Rms size (mm)
17
22
27
32
37
42
47
52
Scanner
xrms
yrms

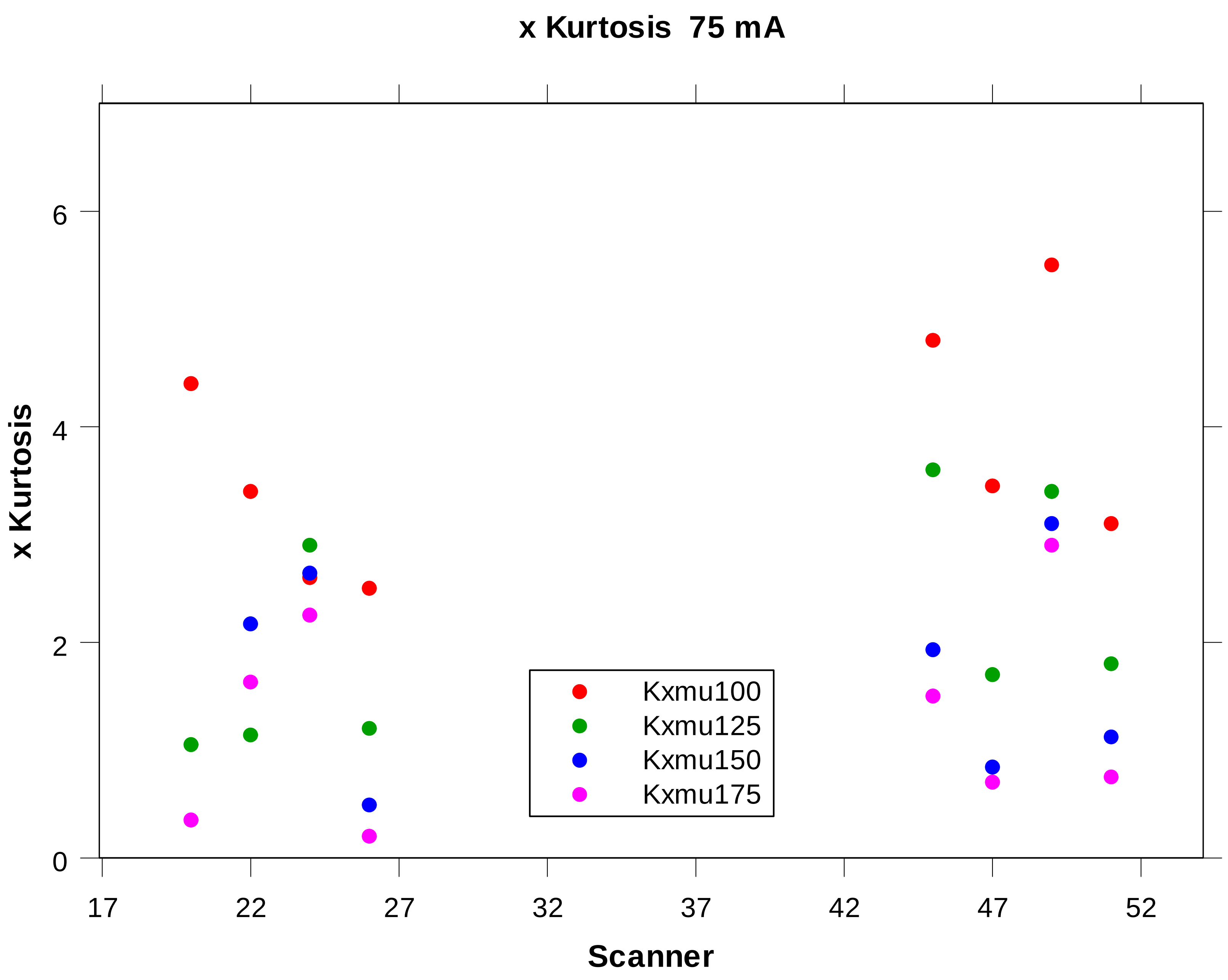

Maximum detectable x amplitude 75 mA
Maximum x amplitude (mm)
scanner
5
6
7
8
9
17
22
27
32
37
42
47
52
mu=1.00(matched)
mu=1.25
mu=1.50
mu=1.75

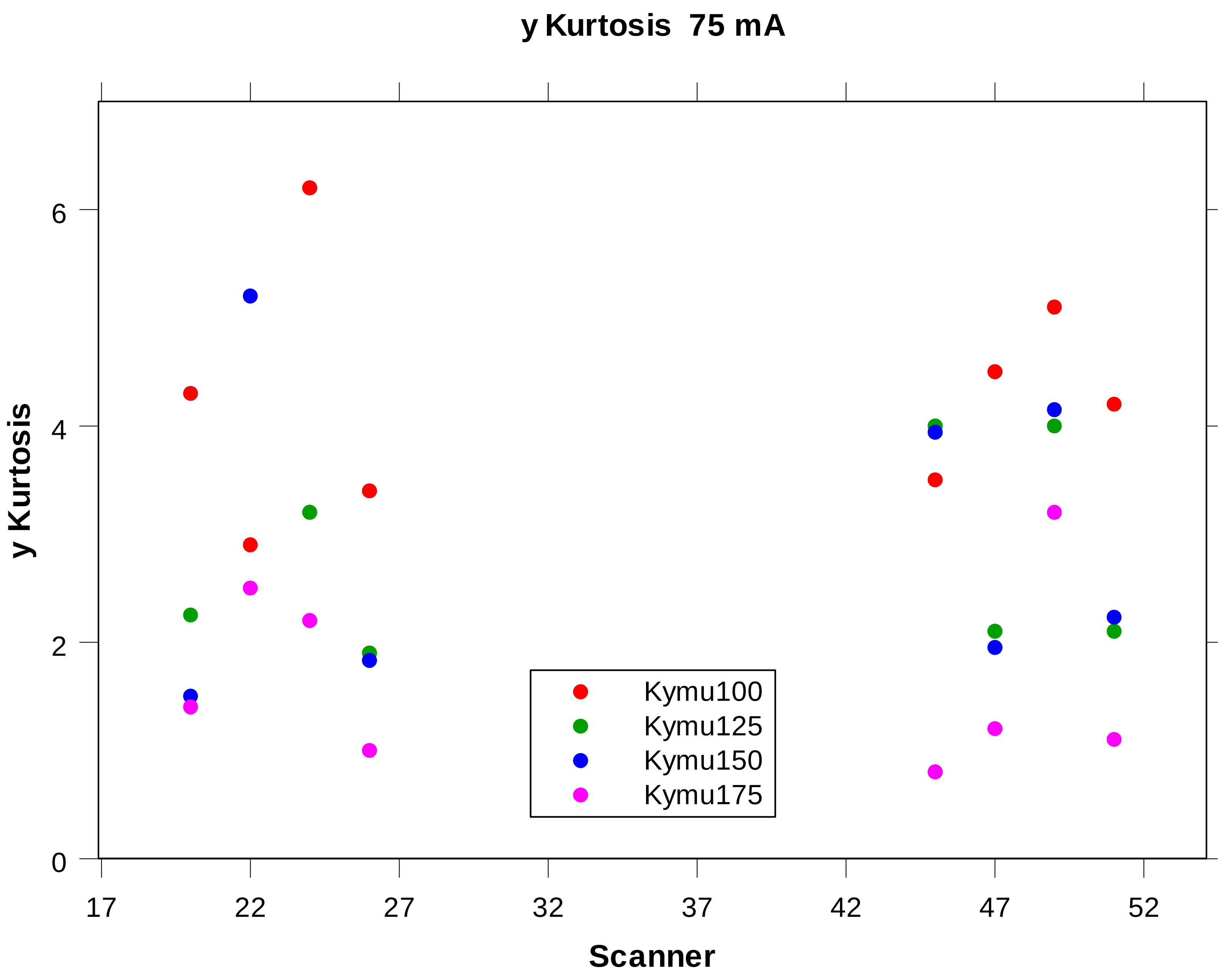

Maximum detectable y amplitude 75 mA
Maximum y amplitude (mm)
5
6
7
8
9
17
22
27
32
37
42
47
52
scanner
mu=1.00(matched)
mu=1.25
mu=1.50
mu=1.75


x-plane rms normalized emittances versus distance
RMS normalized emittance (mm-mrad)
0.0
0.2
0.4
0.6
0.8
1.0
1
3
5
7
9
Distance(m)
mu=1
mu=1.5
mu=1.75
mu=1.5


x-plane rms normalized emittances versus distance
RMS normalized emittance (mm-mrad)
Distance(m)
0.0
0.2
0.4
0.6
0.8
1.0
1
3
5
7
9
mu=1.00
mu=1.75
mu=1.25
mu=1.50


y-plane rms normalized emittances versus distance
RMS normalized emittance (mm-mrad)
Distance(m)
1.0
0.8
0.6
0.4
0.2
0.0
1
3
5
7
9
Eymu1
Eymu125
Eymu175
Eymu150


x Kurtosis 75 mA
x Kurtosis
Scanner
0
2
4
6
17
22
27
32
37
42
47
52
Kxmu100
Kxmu125
Kxmu150
Kxmu175


y Kurtosis 75 mA
y Kurtosis
0
2
4
6
17
22
27
32
37
42
47
52
Scanner
Kymu100
Kymu125
Kymu150
Kymu175

Multiparticle simulations were carried out with different simulation codes.

- LINAC code with standard 2D PIC space-charge subroutine called SCHEFF. (Same routine as used in PARMILA.) Ran 100,000 simulation particles on PC computer.
- IMPACT code with 3D PIC space-charge subroutine. Ran 10 million simulation particle runs on SGI computer at LANL.
- Both simulations use beam distribution based on previous multiparticle simulation through RFQ.
  -RFQ output distribution is adjusted to agree with measured ellipse parameters at RFQ exit.
- Excellent agreement between codes.
- Most of the simulation results are based on the IMPACT code.

Preliminary conclusions from 75 mA multiparticle simulations

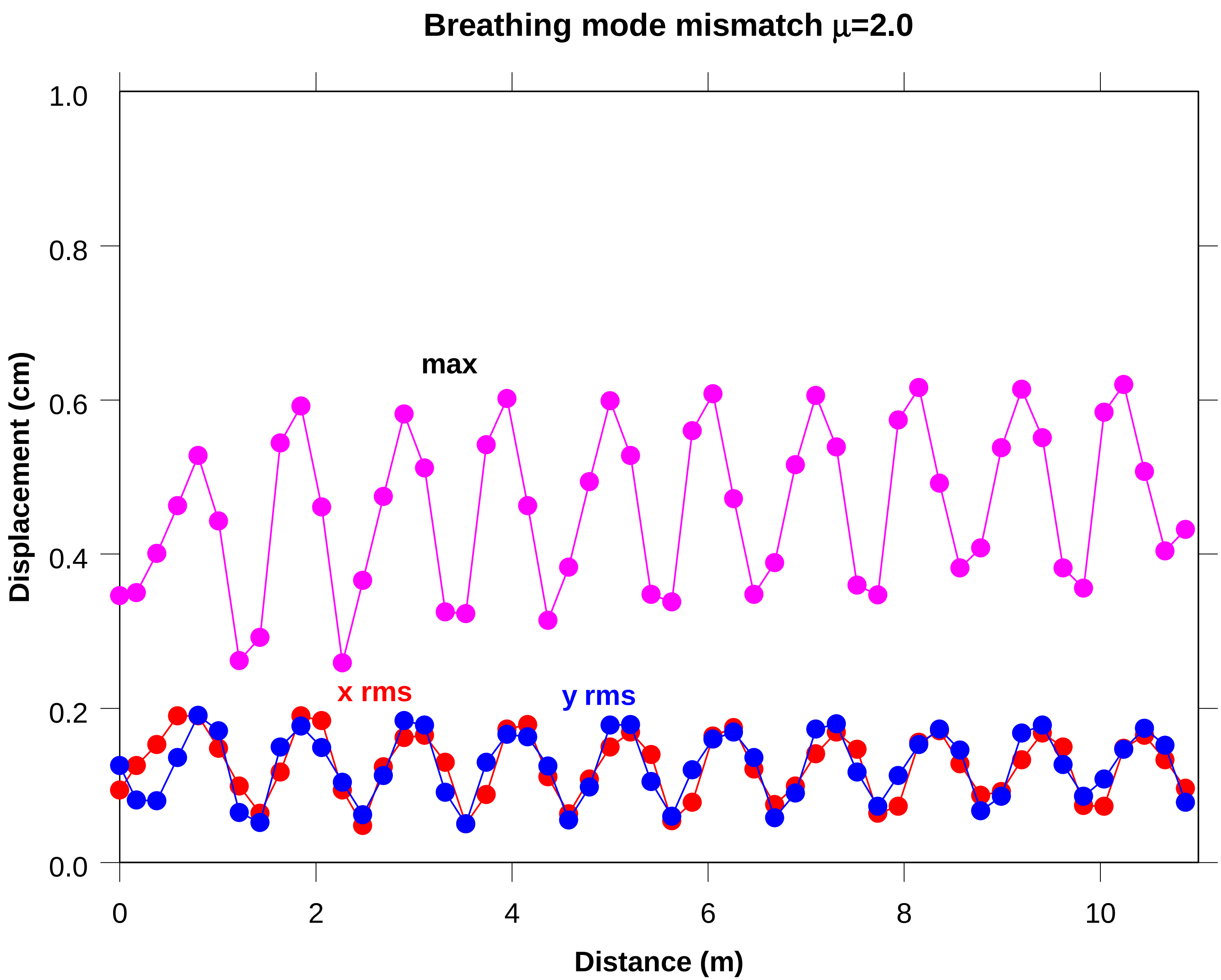
- Measured results are <u>not</u> in good agreement with simple multiparticle simulations using the nominal output beam from the RFQ.
- Multiparticle simulations including lower energy particles, within about 1 MeV below the nominal 6.7 MeV design energy, show shoulders and asymmetries similar to the real data.
- Emittance growth, halo growth, and maximum amplitudes in the transport channel are also similar to the data.
- Precise tests of the simulation codes would require more information about the beam including the off-energy component.

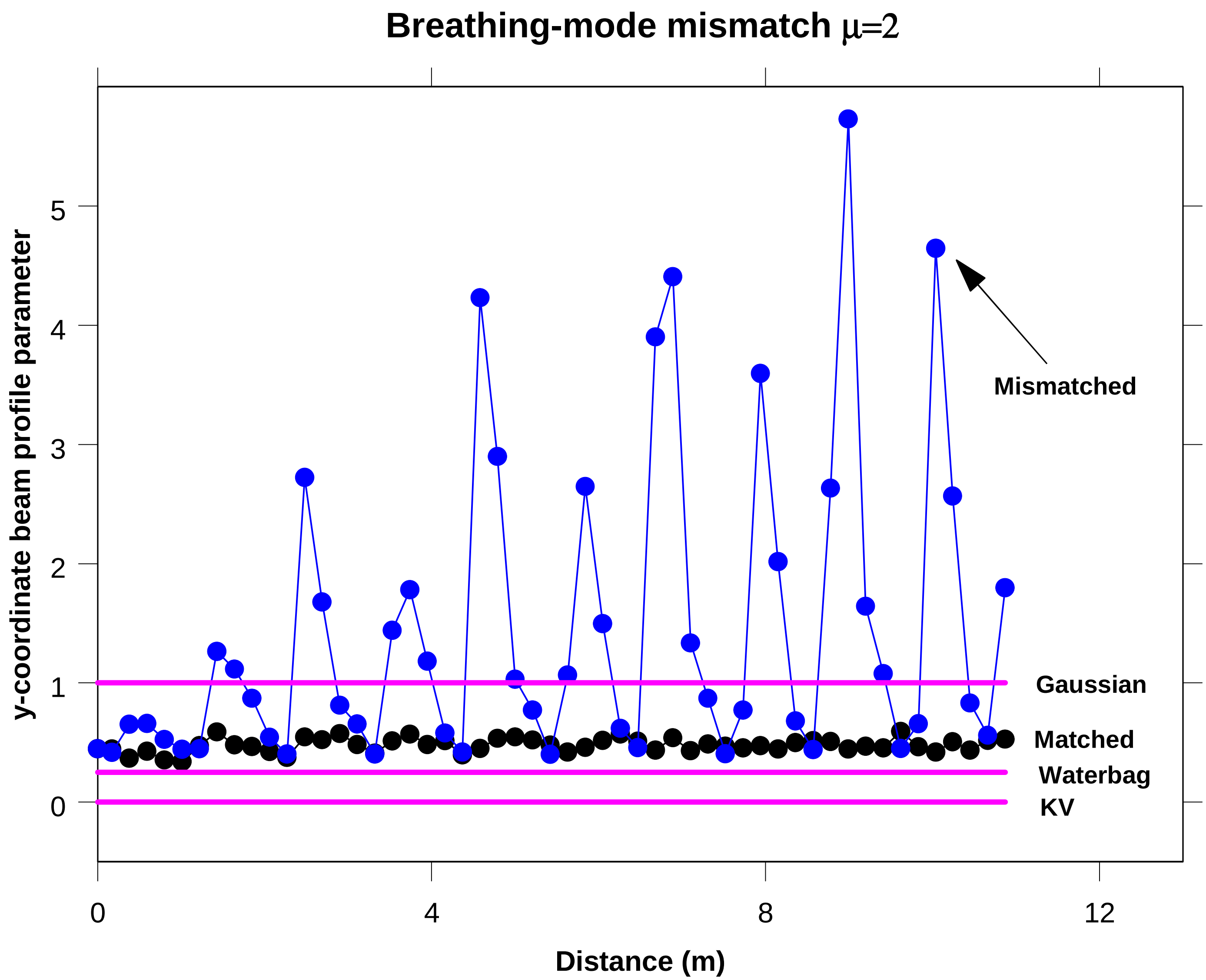
Summary

- The present results at 75 mA are consistent with space-charge forces acting in a mismatched beam which contains a significant fraction, perhaps a few percent, of particles within about an MeV below the nominal RFQ output energy.

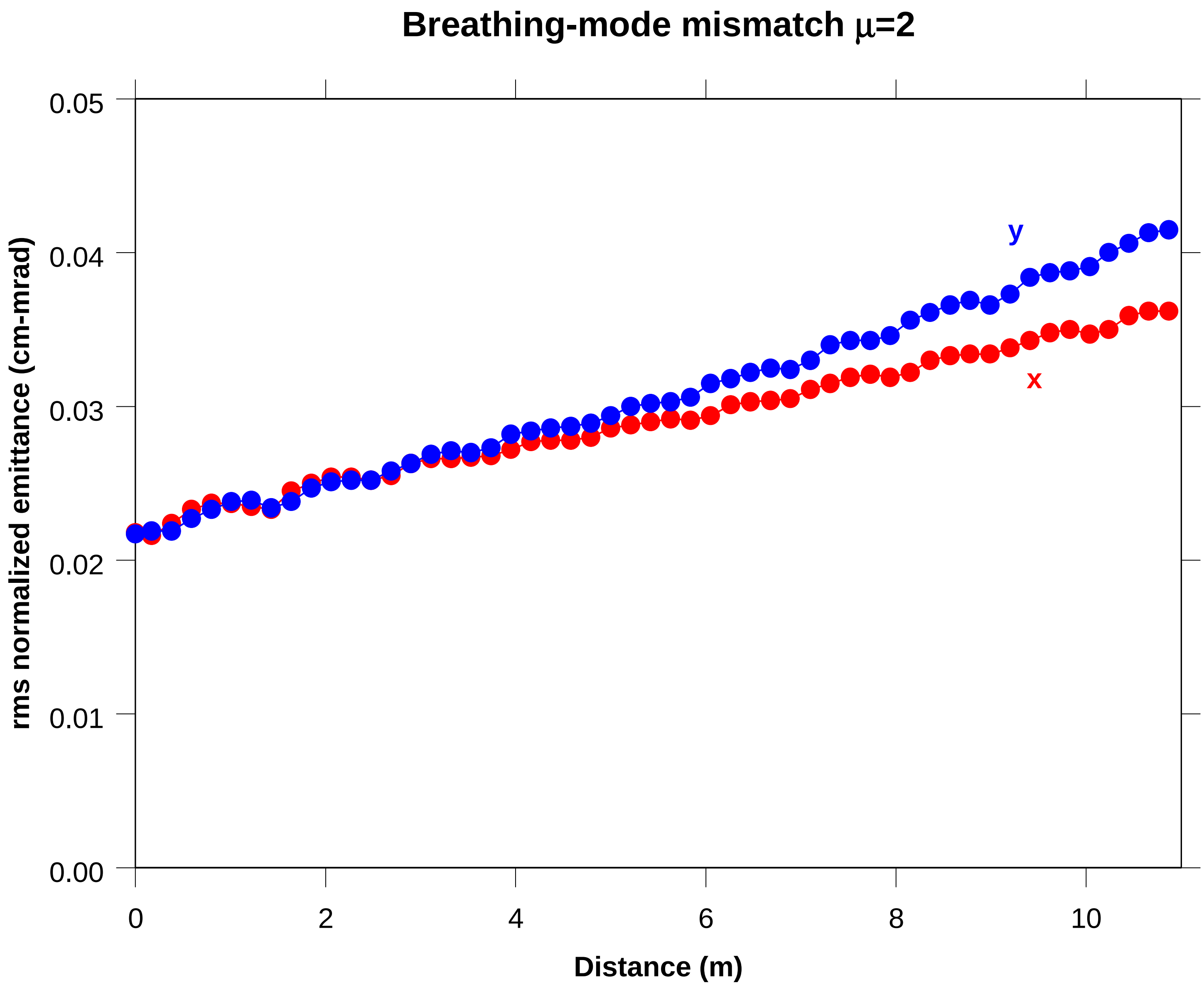
Beam diagnostics

- Beam centroid
- Beam current
  -pulsed current toroids
  -350 MHz bunch current toroids
- Beam Loss
  -differential current
  -CsI scintillator/PM tubes
- Beam Profile Diagnostics
  -Carbon wire for core
  -graphite scraper plates for halo.

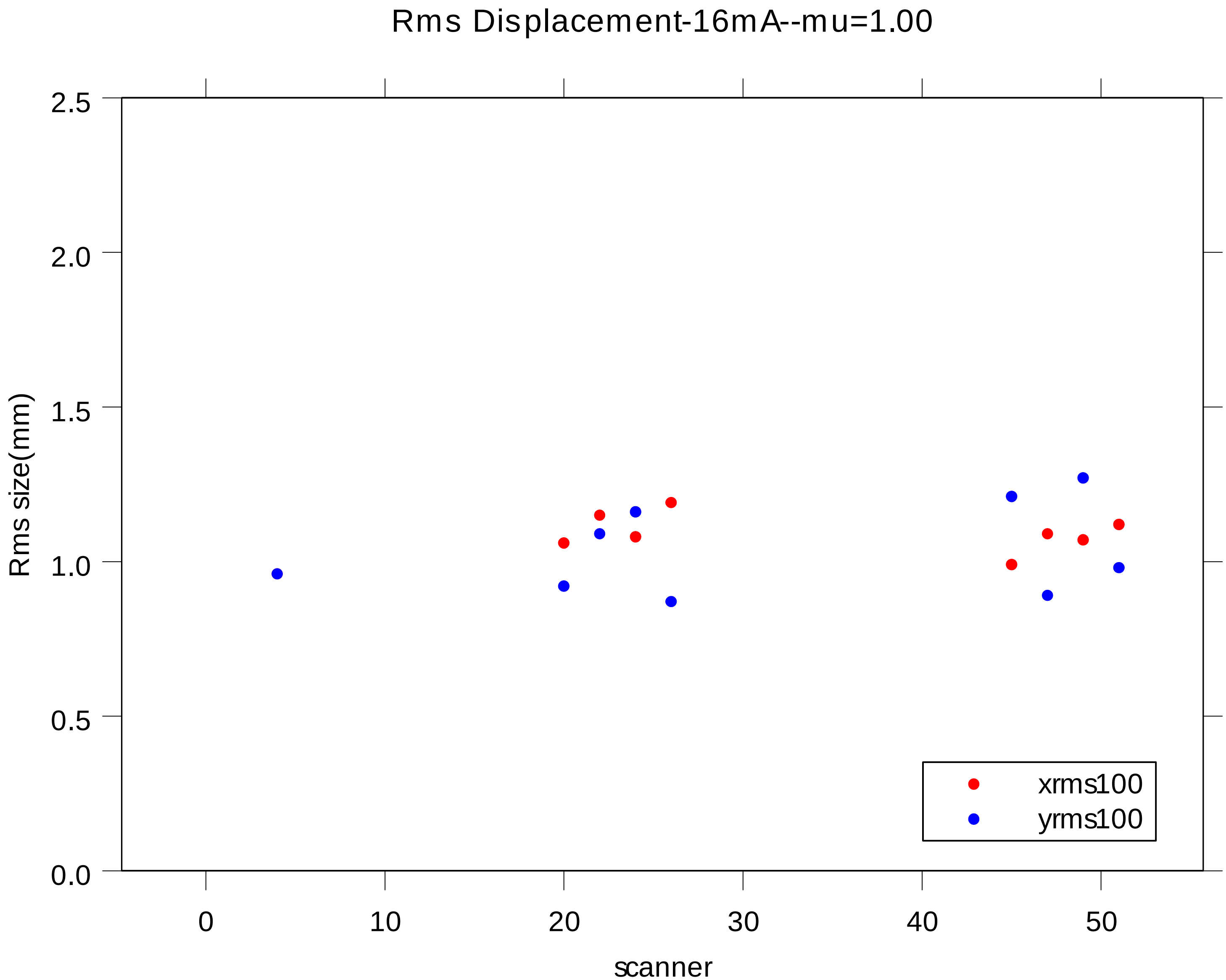

Breathing mode mismatch μ=2.0
max
x rms
y rms
Displacement (cm)
Distance (m)
0.0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8
10



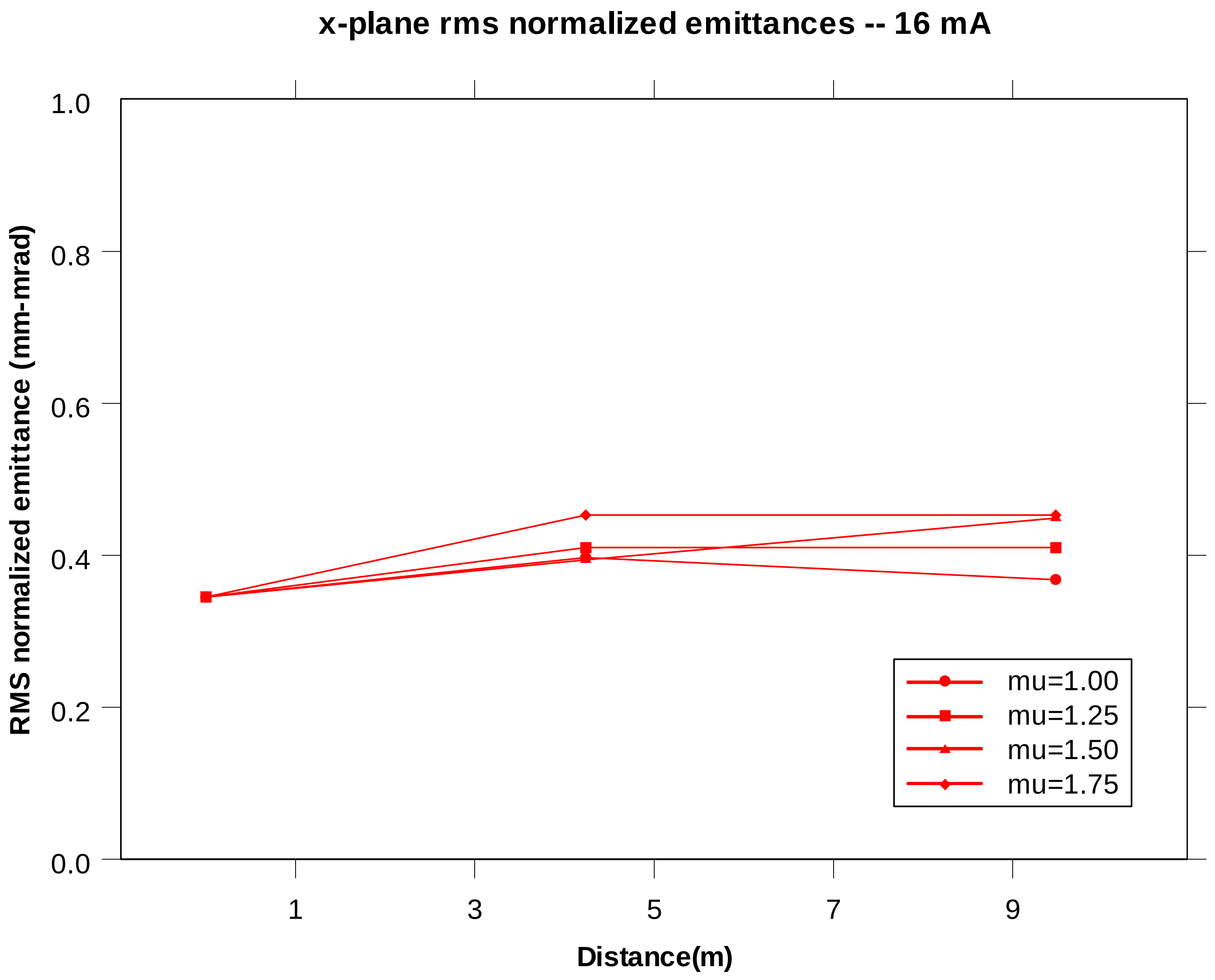
Breathing-mode mismatch μ=2
y-coordinate beam profile parameter
Distance (m)
0
1
2
3
4
5
0
4
8
12
Mismatched
Gaussian
Matched
Waterbag
KV

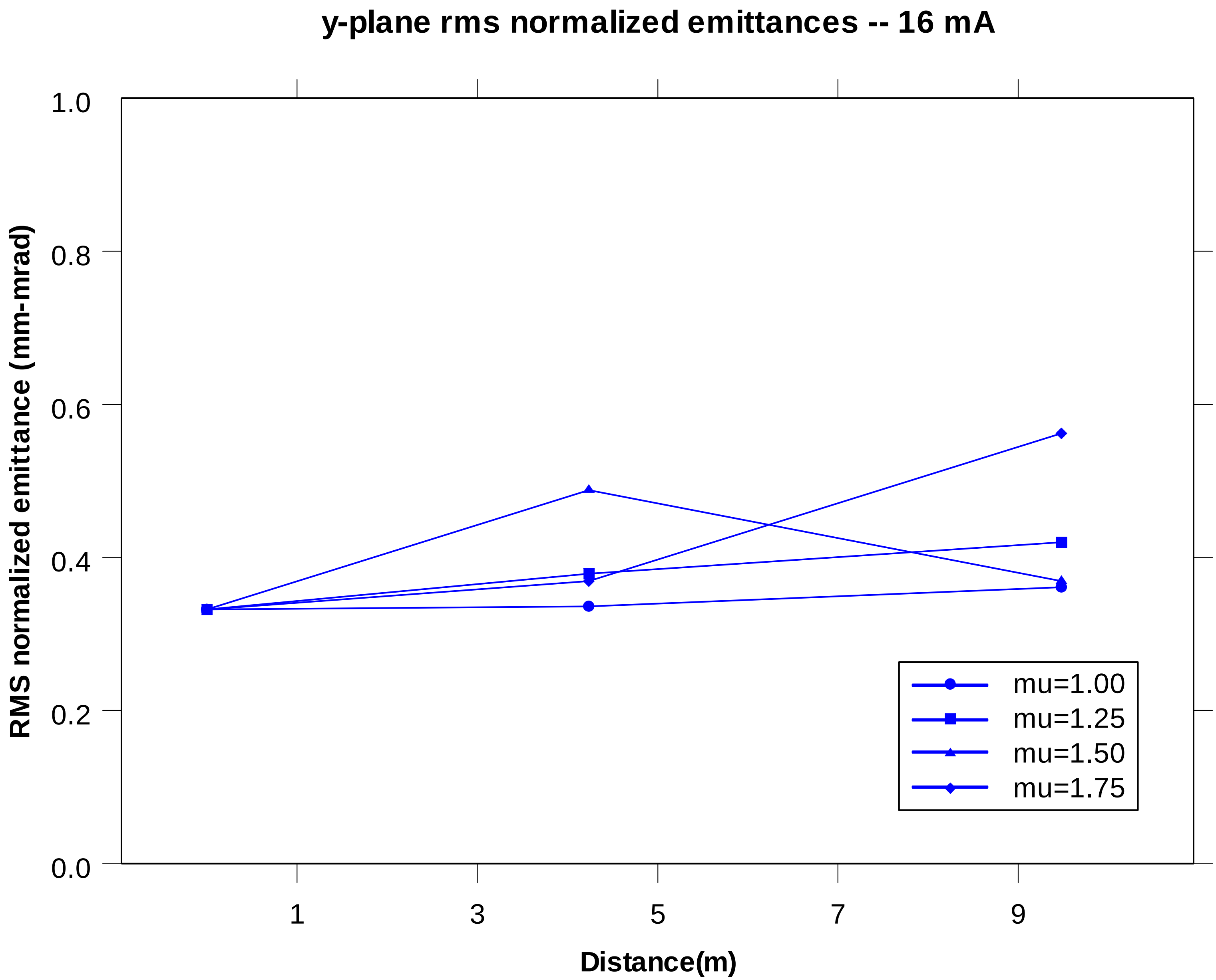


Breathing-mode mismatch μ=2
rms normalized emittance (cm-mrad)
0.00
0.01
0.02
0.03
0.04
0.05
0
2
4
6
8
10
Distance (m)
y
x



Rms Displacement-16mA--mu=1.00
Rms size(mm)
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
scanner
xrms100
yrms100


x-plane rms normalized emittances -- 16 mA
RMS normalized emittance (mm-mrad)
Distance(m)
1.0
0.8
0.6
0.4
0.2
0.0
1
3
5
7
9
mu=1.00
mu=1.25
mu=1.50
mu=1.75



y-plane rms normalized emittances -- 16 mA
RMS normalized emittance (mm-mrad)
1.0
0.8
0.6
0.4
0.2
0.0
1
3
5
7
9
Distance(m)
mu=1.00
mu=1.25
mu=1.50
mu=1.75